Attachment 4

-- Non-Proprietary Version –

"PBMR Design and Heat Removal Preliminary Description"

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PBMR DESIGN AND HEAT REMOVAL PRELIMINARY DESCRIPTION

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LIST OF ABBREVIATIONS USED IN THIS DOCUMENT

Abbreviation or Acronym	Definition
ACS	Active Cooling System
ASME	American Society of Mechanical Engineers
AVR	Arbeitsgemeinschaft Versuchsreaktor (German for Jointly-operated Prototype Reactor)
CCS	Core Conditioning System
DLOFC	Depressurized Loss of Forced Cooling
FHSS	Fuel Handling and Storage System
HTR	High Temperature Reactor
HTR-Modul	High Temperature Modular Reactor (German high-temperature modular reactor design – not built)
MWD/MT	Megawatt days per metric ton
PBMR	Pebble Bed Modular Reactor
PCU	Power Conversion Unit
PFC-3D	Engineering analysis code
PLOFC	Pressurized Loss of Forced Cooling
RCCS	Reactor Cavity Cooling System
RCS	Reactivity Control System
RCSS	Reactivity control system including both RCS and RSS
RPV	Reactor Pressure Vessel
RPVCS	Reactor Pressure Vessel Conditioning System
RSS	Reserve Shutdown System (Neutron absorber system using borated spheres)
RUCS	Reactor Unit Conditioning System
SBS	Start-up Blower System
STAR-CD	analytical code
THTR	Thorium High Temperature Reactor
UHS	Ultimate Heat Sink
VSOP	Very Special Old Program (reactor analysis code)

1. INTRODUCTION

The purpose of this document is to provide a summary description of the Pebble Bed Modular Reactor (PBMR) design and heat removal mechanisms.

The plant design is in the basic design phase. Detailed calculations have been performed as part of examining the feasibility of the project using the basic design considered in that study. Results from some of these calculations are presented in this report. Changes to design details and parameters are likely to be made as part of the detailed design process, which is just beginning. These changes will likely affect the analytical results. Numerical values presented in this report are considered to reflect the order of magnitude of values that will be seen in the final design, but final design calculations have yet to be performed. The general layout and operating characteristics, as described herein, are not expected to change.

Section 2 of this report describes the general configuration of PBMR plant systems. It also provides a more detailed, but still summary, description of core design.

Section 3 of this report describes the systems and natural processes by which heat will be removed from the PBMR core under normal operating and upset conditions.

2. PLANT DESIGN

2.1 GENERAL

The PBMR builds upon design and operational experience obtained by the Germans in operating similar reactors (AVR and Thorium High Temperature Reactor [THTR]). The High Temperature Modular Reactor (HTR-Modul) unit design was used as a reference in developing the conceptual PBMR design on which feasibility was evaluated. The characteristics of inherent safety and passive heat removal are emphasized in the plant design.

Several changes were made from the controversial HTR design. These include:

- Control elements have been placed in the reflector rather than in the fueled region.
- The height/diameter ratio of the core has been changed from 1:1 to approximately 3:1. This change improves the capability to remove decay heat passively. Caution was exercised to avoid exceeding a length that would introduce reactivity instabilities due to Xe poison swing.
- A central graphite column (reflector) is used. This permits achieving greater power levels than the 80 MW of HTR-Modul.

These changes result in additional height and a slender, tall reactor. The resulting annular core and central reflector results in the peak neutron flux being displaced towards the outer reflector, where the control elements are located.

The core diameter is 3.5 meters, reflector -to-reflector. The central column is 1.75 meters in diameter. The effective height of the core is approximately 8.5 meters.

2.2 Primary Coolant Flow Circuit

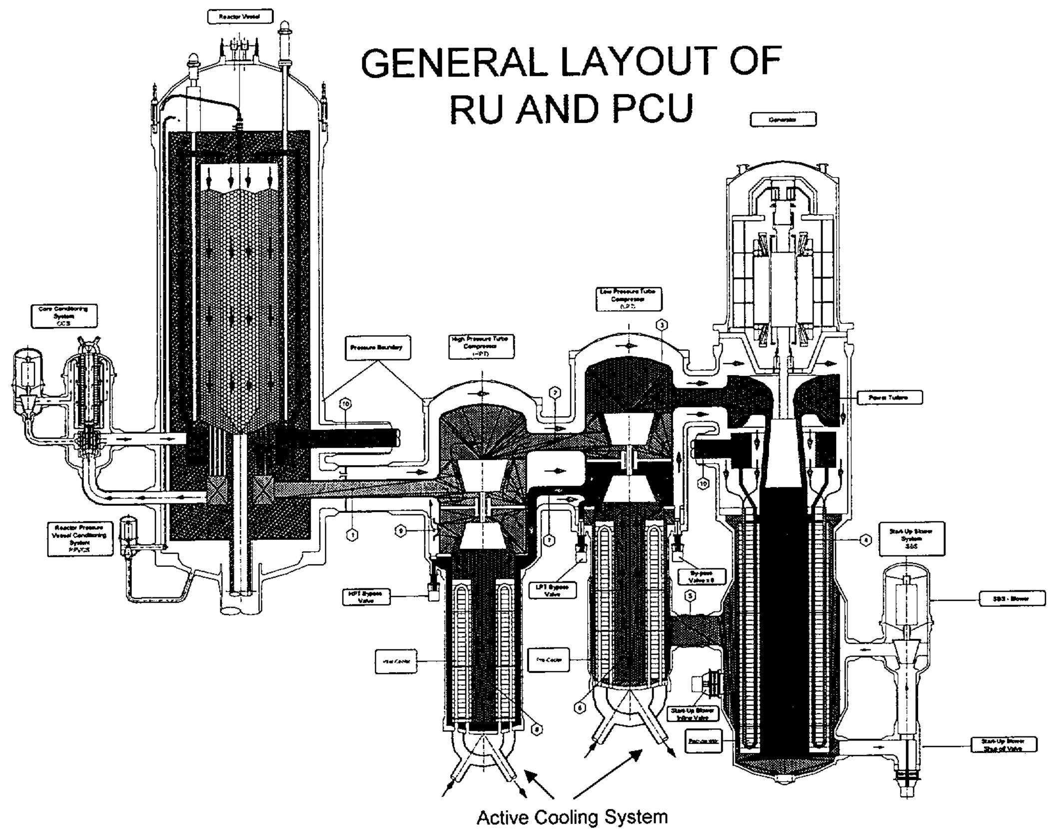


Figure 2.2-1: PBMR SEMI-SCHEMATIC

Figure 2.2-1 presents a conceptual schematic of the PBMR reactor plant. The major components include the Reactor Pressure Vessel (RPV), high- and low-pressure turbo compressors, the power turbine and generator, recuperator and pre- and intercoolers. Support systems, used during shutdown and startup periods, include the Start-up Blower System (SBS), Core Conditioning System (CCS), and Reactor Pressure Vessel Conditioning System (RPVCS). The latter two systems are combined in a single unit called the Reactor Unit Conditioning System (RUCS).

Under normal operation, helium gas enters the core through slits at the top. It flows downward, through the pebble bed of the annular core and through the central reflector, and exits into a gas plenum at the bottom. Gas temperatures are expected to vary considerably at the core outlet, ranging from the order of 650 °C beneath the central reflector to 900 to 1100 °C below the fueled region.

Helium mass flow rate is higher in the fueled region (a design feature intended to reduce erosion of the coolant channels in the upper graphite structures). The mixed mean core outlet temperature is 900 °C. The final design will include a mixing chamber, to mix the helium and provide a more uniform outlet temperature. This action is being taken to avoid stratification of the helium flow and resulting operational concerns, including blade striping of the turbo units.

Helium gas exiting the outlet plenum flows into the high-pressure turbo compressor and expands. It then passes into the low-pressure turbo compressor and the power turbine. After expansion in the power turbine, it returns to the reactor co re via the recuperator, the pre- and intercoolers and again the recuperator. Helium inventory is adjusted to accommodate changes in power level, using a system not depicted on ***Figure 2.2-1***.

The cooling system serving the secondary sides of the two coolers is a pumped water system. The pressure in the cooling system is just above atmospheric. Helium operating pressure is on the order of 42 to 50 bar, preventing any water ingress in the event of leaks in the heat exchangers.

The SBS is an in-line blower used to charge the Brayton cycle during startup operations. Bypass valves serve to bypass the high- and low-pressure compressors during startup and some transient conditions. The SBS is capable of operating up to a core power of approximately 20 percent.

The RPVCS circulates gas between the core barrel and the RPV. This serves to maintain the RPV wall at a more even temperature, eliminating hot spots.

The CCS is a small forced-cooling system capable of removing full decay heat. It is used during maintenance periods in which the RPV must be isolated from the remainder of the Power Conversion Unit (PCU).

The Reactor Cavity Cooling System (RCCS) (not depicted) consists of 45 tanks arrayed around the reactor vessel in the reactor cavity.

2.3 Reactor Pressure Vessel

PBMR RPV
Layout

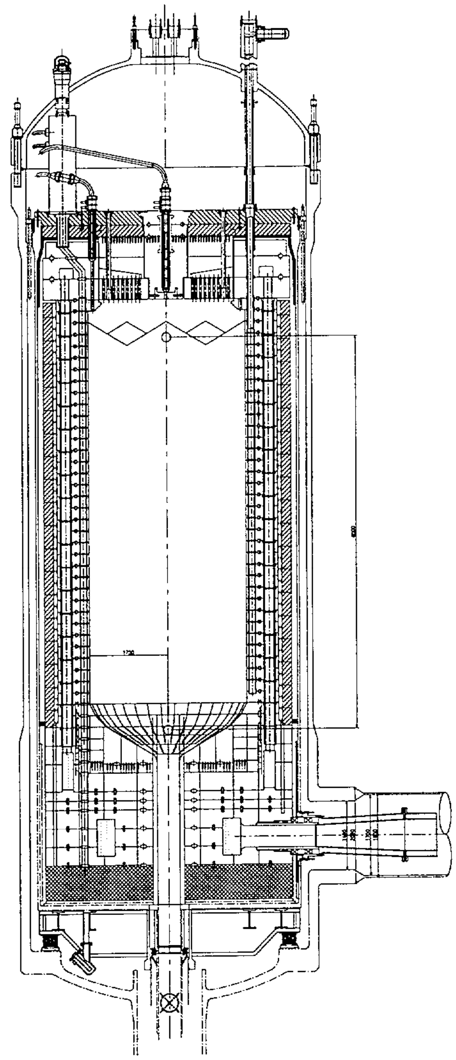


Figure 2.3-1: PBMR RPV LAYOUT

Figure 2.3-1 depicts the physical layout of the RPV. The feasibility study design is depicted. Some design improvements have been made since this drawing was prepared. Principal among these is elimination of a carbon thermal barrier, depicted on this figure, protecting the RPV wall. This thermal barrier will not be incorporated in the final design, since material temperatures are not expected to exceed Code Case limits.

An inlet plenum at the bottom connects to the piping returning helium from the PCU. Radial flow channels are used to direct helium preferentially into the annular core, as described above.

The Reactivity Control System (RCS) includes control rods and small absorber spheres, both with B_4C absorber. Channels for the rods and absorber spheres are situated in the reflector, at the location of the flux peak. There are a total of 35 borings in the outer reflector for reactivity control, 18 for control rods and 17 for absorber spheres. The control rods are chain-driven, consisting of two 9 -rod banks of half-length rods (described further below).

Fuel and moderator spheres are loaded via loading tubes arrayed around the top of the reactor vessel. There are 9 fuel loading tubes and a single moderator tube for the central reflector column. Fuel and moderator spheres are discharged into a chute at the bottom of the reactor vessel.

2.4 Fuel Handling and Storage System

PBMR
FHSS
Schematic

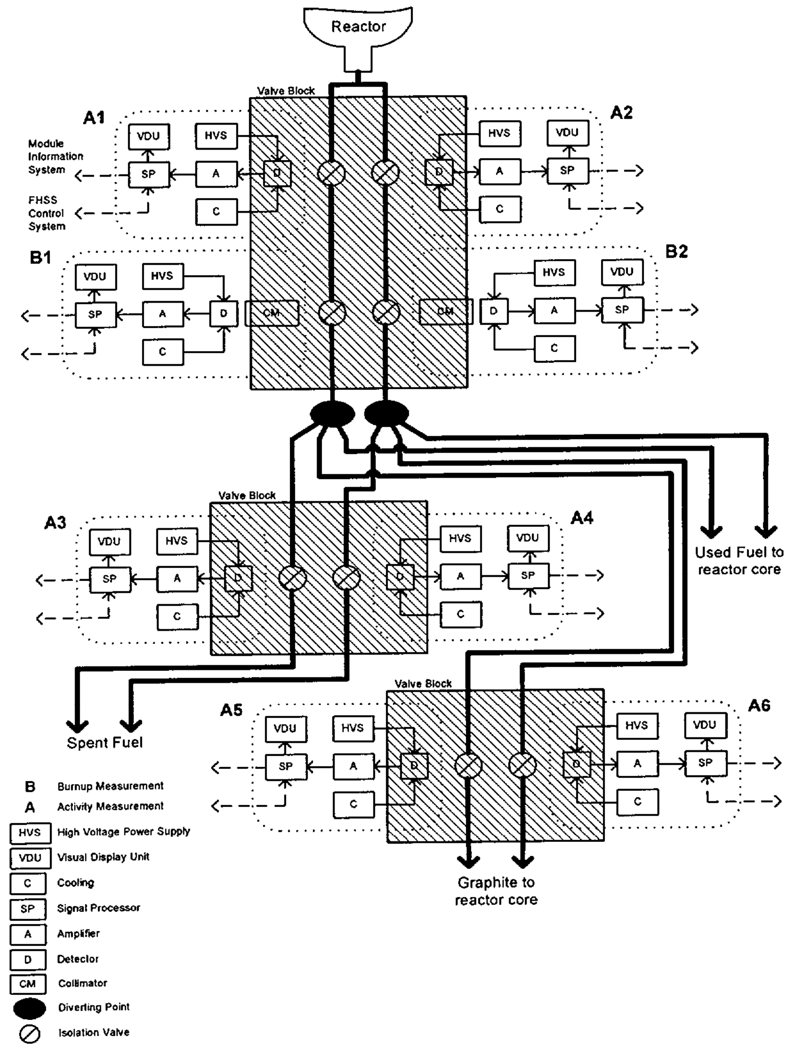


Figure 2.4-1: PBMR FHSS Schematic

The Fuel Handling and Storage System (FHSS) is depicted in ***Figure 2.4-1***. The system directs spheres removed from the core through a series of valve blocks. The design of the valve blocks is taken directly from the German High Temperature Reactor (HTR) design, and was used successfully on THTR. The system is designed for high-pressure operation, approximately 70 bars. The system collects discharged spheres, monitors them to discriminate between fuel and moderator, and to determine burn-up of fuel spheres, and routes them to one of several destinations.

The decay time to the monitoring station in the first valve block is approximately 40 hours. This allows decay of short-lived fission products. A gross gamma measurement can therefore be used to discriminate between fuel and moderator spheres. A second measurement uses a gamma spectrometer and Germanium detector to identify the cesium peak and determine burn -up of fuel spheres.

Based on the results of the monitoring in the first valve block, moderator spheres are recycled, re-usable fuel is returned to the core, and spent fuel is routed to the spent fuel tanks. Moderator spheres are subjected to a second measurement to verify that fuel has not been misrouted into this circuit. Any fuel detected in this block can be re-routed.

The precise criteria for discriminating between "spent" fuel and re- usable fuel are still being determined. Additional monitoring, for other peaks or using spiking, may be needed for the initial, low-enriched fuel spheres. In addition, the specific increment below 80,000 MWD/MT that will be used to determine whether a fuel sphere can be recycled or removed from the cycle is yet to be determined. Consideration is being given to reducing the planned number of cycles for an individual pebble from 10, as considered in the feasibility design study, to 6. This will also have an effect on core flux peaking.

Adjusting the rate at which spheres are discharged from the core, and thus the number of cycles expected for an individual fuel sphere, can be done in a number of ways. One or two discharge channels can be used. The speed of the unloading machine can be adjusted. Unloading can be conducted on a varying number of shifts.

2.5 Pebble Behavior in The Core

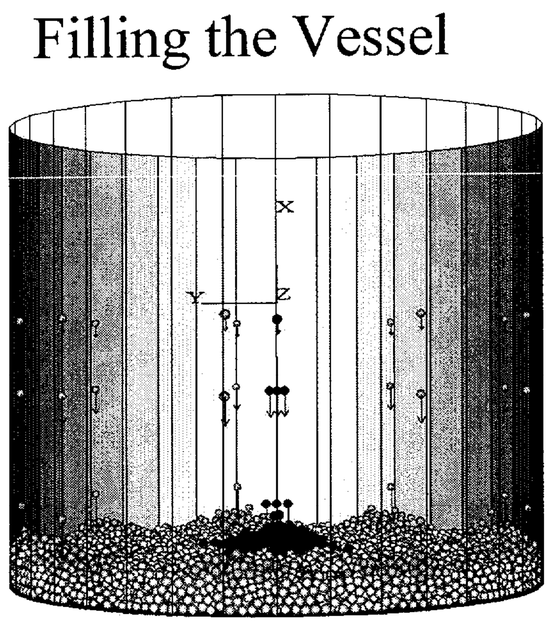


Figure 2.5-1: FILLING THE VESSEL

Pebble flow experiments were conducted in Germany to improve knowledge of how they flow through the core. Flow has been further assessed in South Africa using a computer simulation. Model results were compared with the German experiments and were found to be within 10 percent. The simulation model considers the total core. It models each individual pellet. The resulting calculation was performed on four parallel DEC alpha computers and required 4 months to perform. Benchmarking of pebble flow is still under consideration, but some method of validation and verification must be applied to the VSOP code pebble flow model.

Core Sphere Flow Analysis

Detailed analysis of the dynamics of the spheres in the upper core volume are completed. The behavior of the spheres in this region determines the formation of the two zone core with a mixing zone.

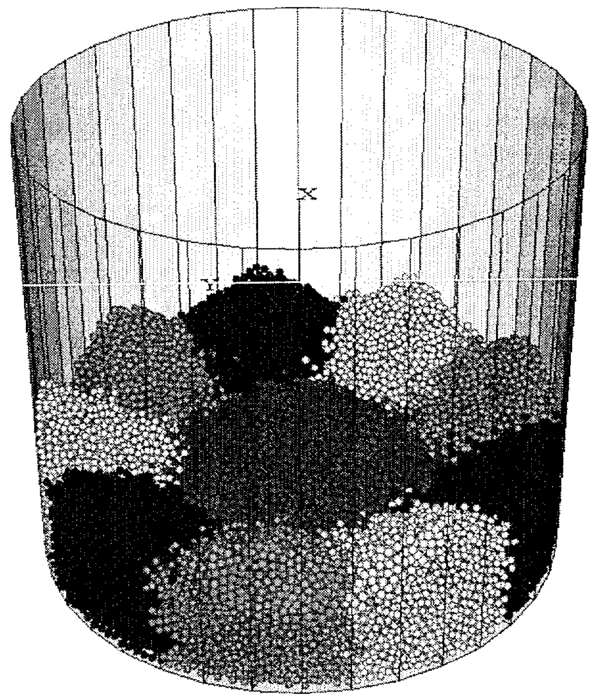
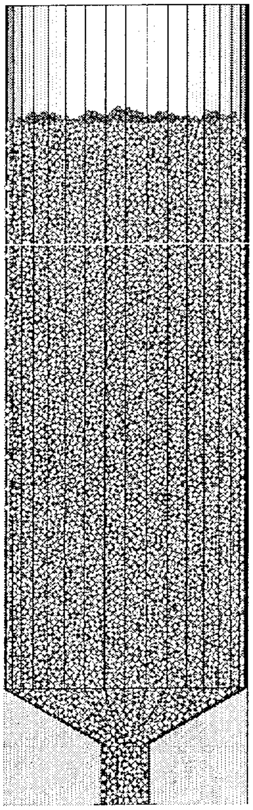


Figure 2.5-2: CORE SPHERE FLOW ANALYSIS

Loading of the core to criticality will start by loading from the top onto a graphite bed. The annular core and central reflector column will form based on the positioning of pebbles as loaded. The size of the central reflector, and of the mixing zone, is strongly defined by the manner in which pebbles are loaded. The fuel handling system design "zeros" the velocity of each sphere before it is dropped, in order to minimize bounce and potential effects on the size of the mixing zone.

Core Sphere Flow



The motion of the fuel and graphite spheres in the PBMR core is an important area of study. Large scale simulations using the Discrete element modeling technique have been carried out.

The picture on the right shows simulation results for the core simulation, these results show a clearly defined three zone core.

A validation exercise has been undertaken. Agreement between the PFC-3D simulations and the ANNABEK experiment was within 10%.

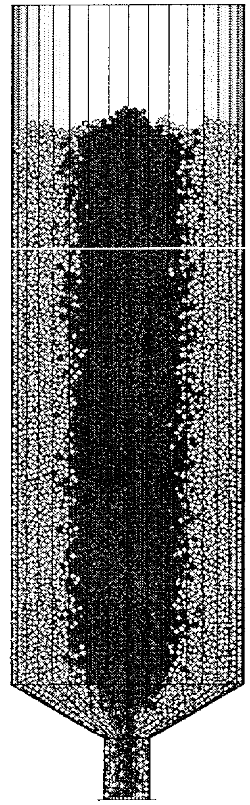


Figure 2.5-3: CORE SPHERE FLOW

[PROPRIETARY Figure intentionally Removed]

Figure 2.5-4: FLOW LINES

Figure 2.5-4 **[PROPIETARY** - Figure note intentionally removed]

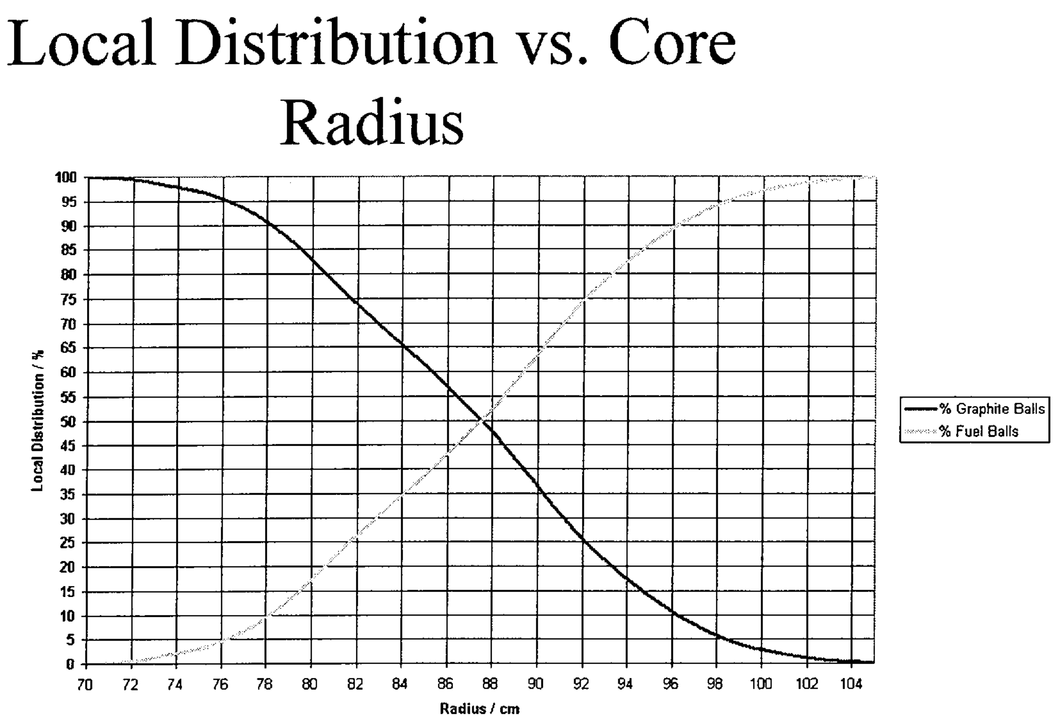


Figure 2.5-5: LOCAL DISTRIBUTION VS. CORE RADIUS

The results of the calculation show that there is a clearly defined central column throughout the height of the core, with a mixing zone of known quality. The mixing zone is calculated to have a thickness of 22 cm. The centre of the zone is at a theoretical location of 87.5 cm from the centre of the re actor vessel. ***Figure 2.5-5*** displays the distribution of fuel and moderator within the mixing zone. The overall ratio of graphite to fuel in the mixing zone is 48.5/51.5. The calculations showed no individual or group of fuel pebbles within the central column, nor graphite within the fueled zone, outside of the mixing zone.

2.6 CORE ANALYSIS

The VSOP code system is used for the numerical simulation of the physics of the reactor. It requires input models for fuel, geometry, pebble flow, and core composition. Calculations are performed for equilibrium and/or initial core conditions. The calculation is done in time steps, and the status is preserved for future calculations subsequent time steps.

Calculations have been performed using 5 channels. Twenty percent of the total volume of spheres are assumed loaded in each channel: graphite only in channel 1, a 50/50 mixture of fuel and graphite in channel 2, and fuel alone in channel 3. After mixing, spheres are assumed to be mixed and available for reloading in any appropriate channel.

VSOP RU Model

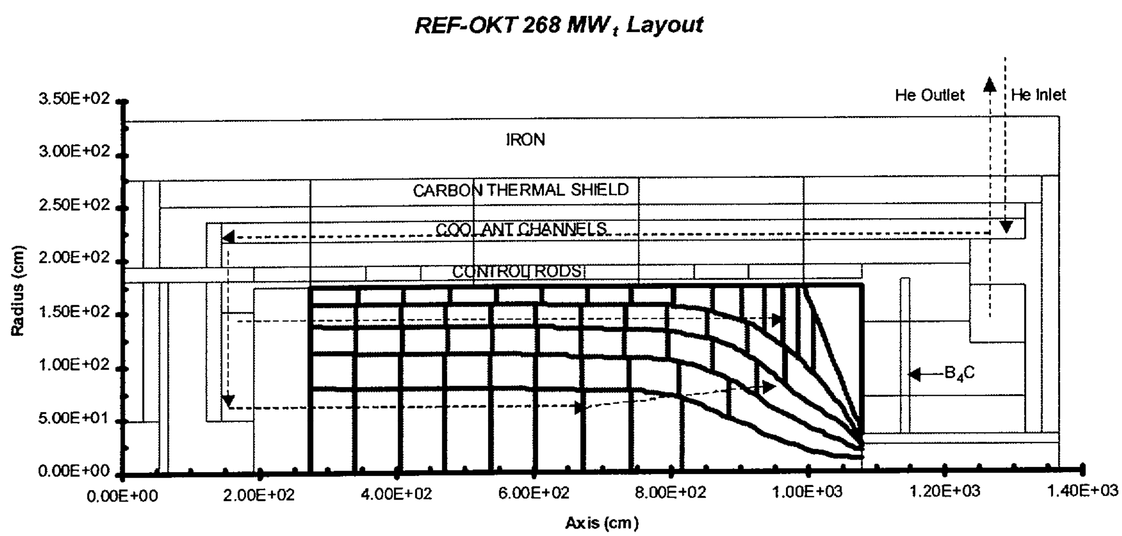


Figure 2.6-1: VSOP REACTOR UNIT MODEL

Figure 2.6-1 shows the reactor core, core structures and vessel model used in the VSOP calculations performed during the feasibility study. The reactor is shown on its side, and includes the thermal shield– then considered in the calculations, but since eliminated from the design. [**PROPRIETARY** – Information regarding modeling results are intentionally removed].

The calculation logic used in VSOP is graphically depicted in ***Figure 2.6-2***.

Calculational Logic

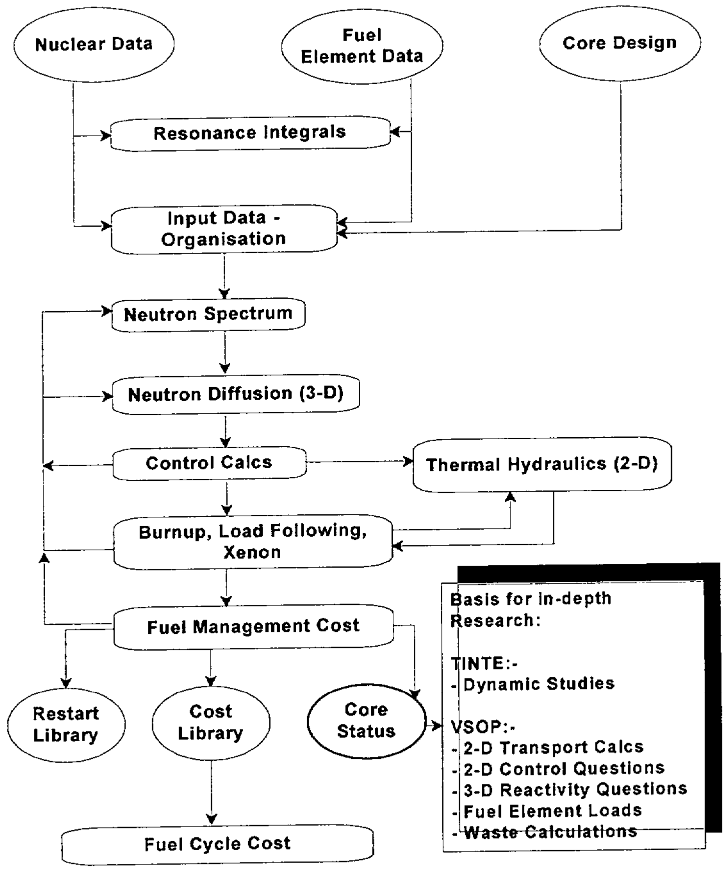


Figure 2.6-2: CALCULATIONAL LOGIC

The temperature coefficients of reactivity calculated for the PBMR are provided in ***Table 2.6-1***. The overall temperature coefficient is strongly negative. (The coefficients, as derived, are isothermal, which is conservative. Further refinement will be made during detailed design).

Table 2.6-1: TEMPERATURE COEFFICIENTS

VSOP Option	2D	3D
Temperature coefficients at operating $\Delta k_{eff}/°C$ conditions:		
Fuel (Doppler coefficient of ^{238}U)	-3.28 E-5	-3.25 E-5
Moderator in fuel part of the core	-3.30 E-5	-3.40 E-5
Central Graphite Zone	+0.93 E-5	+0.82 E-5
Outer reflectors	+1.48 E-5	+1.40 E-5
Total	-4.17 E-5	-4.43 E-5

Damage at the reflector interface is a function of fast flux, and thus that parameter is calculated. Results for various axial positions are displayed in ***Figure 2.6-3***. The radial thermal and fast flux profiles at 415 cm from the top of the core are shown in ***Figure 2.6-4***.

Radial Fast Flux Distribution at Various Axial Positions

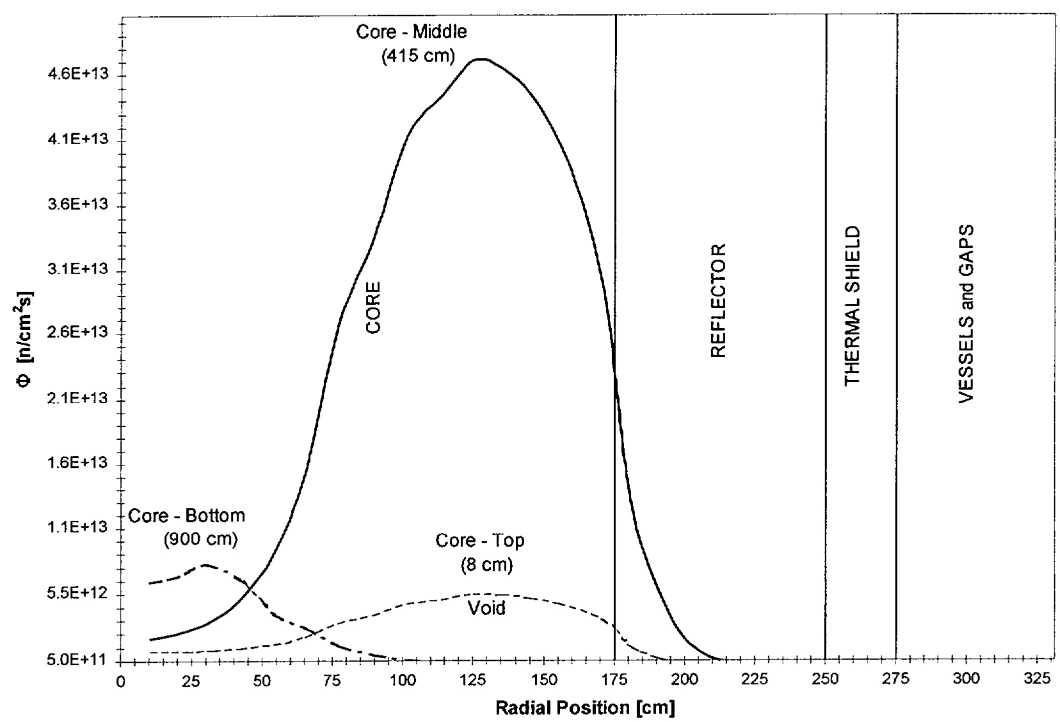


Figure 2.6-3: RADIAL FLUX DISTRIBUTION AT VARIOUS AXIAL POSITIONS

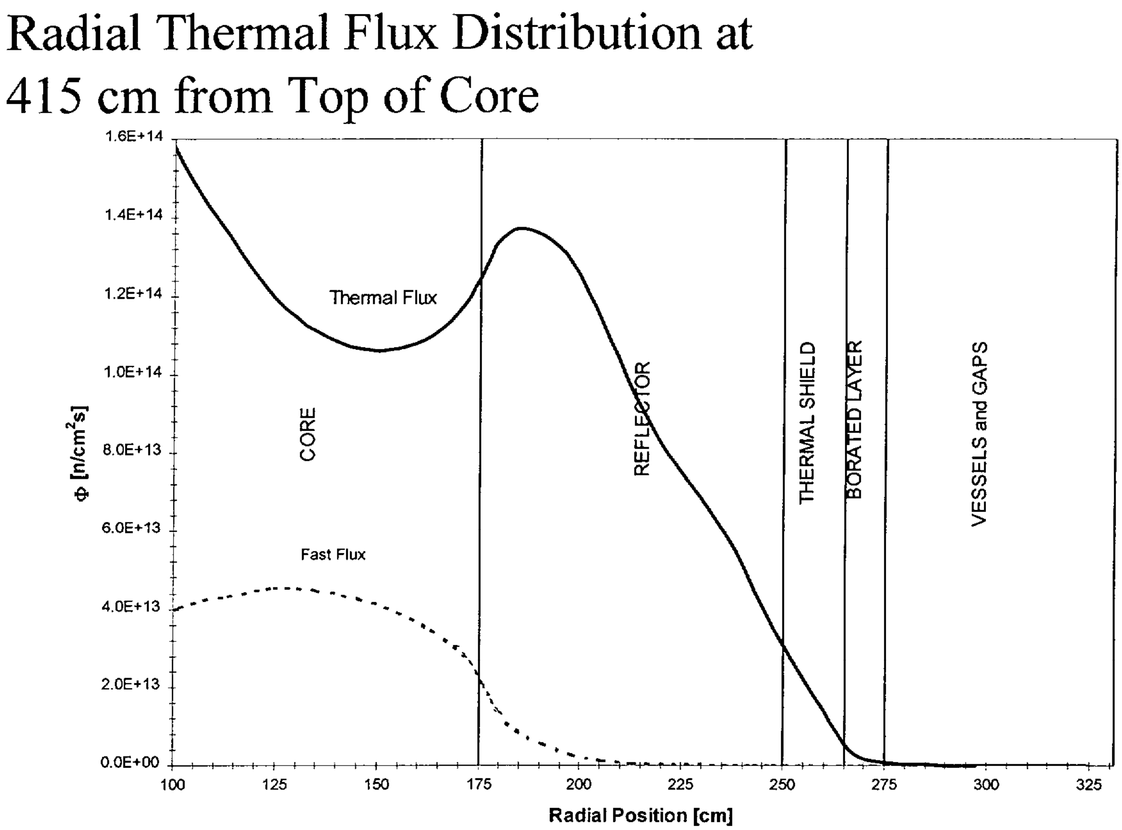


Figure 2.6-4: RADIAL THERMAL FLUS DISTRIBUTION AT 415 cm FROM TOP OF CORE

2.7 Reactivity Control

The Reactivity Control and Shutdown System (RCSS) consists of control rods called the RCS and Reserve Shutdown System (RSS) using small absorber spheres. The RCS has 2 banks of 9 half-length control rods each. The RSS, when discharged, fills 17 reflector borings with absorber spheres for the full height of the core. The inserted position of both elements is depicted in ***Figure 2.7-1***. The upper bank of control rods shadows the lower, as depicted on the figure. The effectiveness of each of the RCSS elements is displayed in ***Figure 2.7-2***.

RCSS Position: Inserted

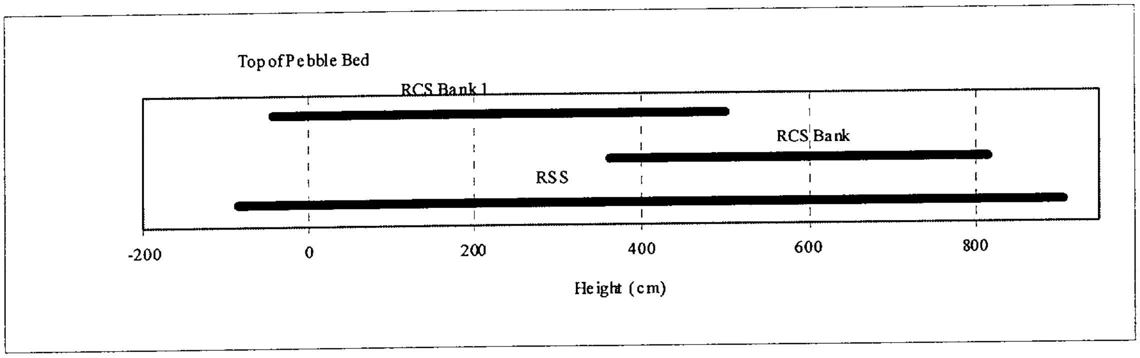


Figure 2.7-1: RCSS POSITION INSERTED

Figure 2.7-2: RCSS CHARACTERISTICS

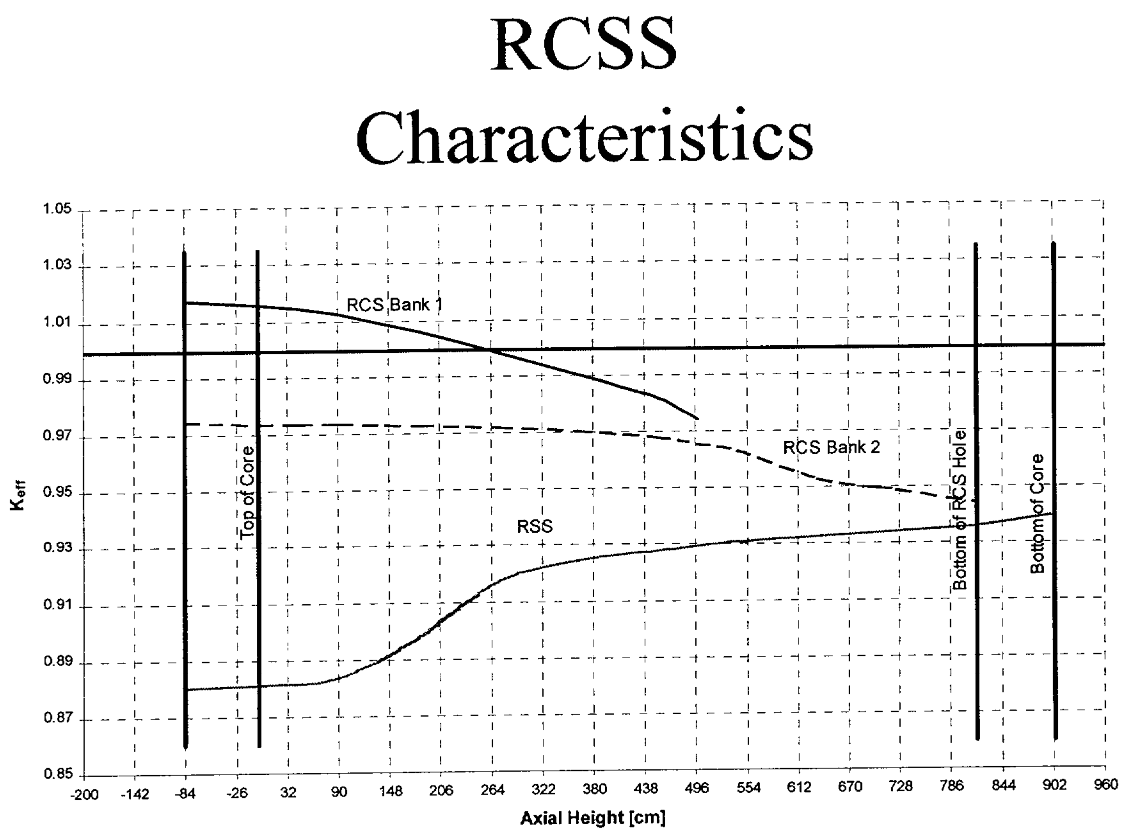


Table 2.7-1*: CONTROL AND SHUTDOWN REACTIVITY BALANCE*

Requirements $\Delta k_{eff}/k$	Value
Operation -> 50 °C	+0.0318
Decay of Xe-135	+0.0490
Decay of other isotopes over 30 days	Neglected conservatively
Xe-override (100-40-100%)	+0.012
Uncertainties	+0.008
Total	+0.101
Capability (9x5.823m top & 9x5.823 bottom) $\Delta k_{eff}/k$	
9 top RCS in side reflector	-0.0429
9 bottom RCS in side reflector	-0.0341
16 RSS in reflector (18 RSS)*	-0.0540 (-0.0595)
Uncertainty	+0.0066 (+0.0068)
Total	-0.1244 (-0.1297)
Reactivity Shutdown Margin	-0.0234 (-0.0287)

Note: *Due to symmetry of the calculation model, the reactivity value of 17 RSS must be interpolated from the calculated value of 16 and 18 RSS. An odd number of RSS are present, because the boring above the helium outlet channel cannot be used.*

Uncertainties of 8 and 5 percent are used in the reactivity balance (***Table 2.7-1***) based on the German practice. They are to be verified experimentally during startup.

For a xenon transient, the reactor is designed to assure that complete withdrawal of the 9 partially inserted control rod bank would not result in core temperatures exceeding 1600 °C. The reactivity worth of the rods is therefore limited to 1.3% Δk/k. This means that the maximum xenon transient that can be overridden is a 100-40-100 percent load following transient. The profile of that transient is shown in ***Figure 2.7-3***.

Xenon Transient

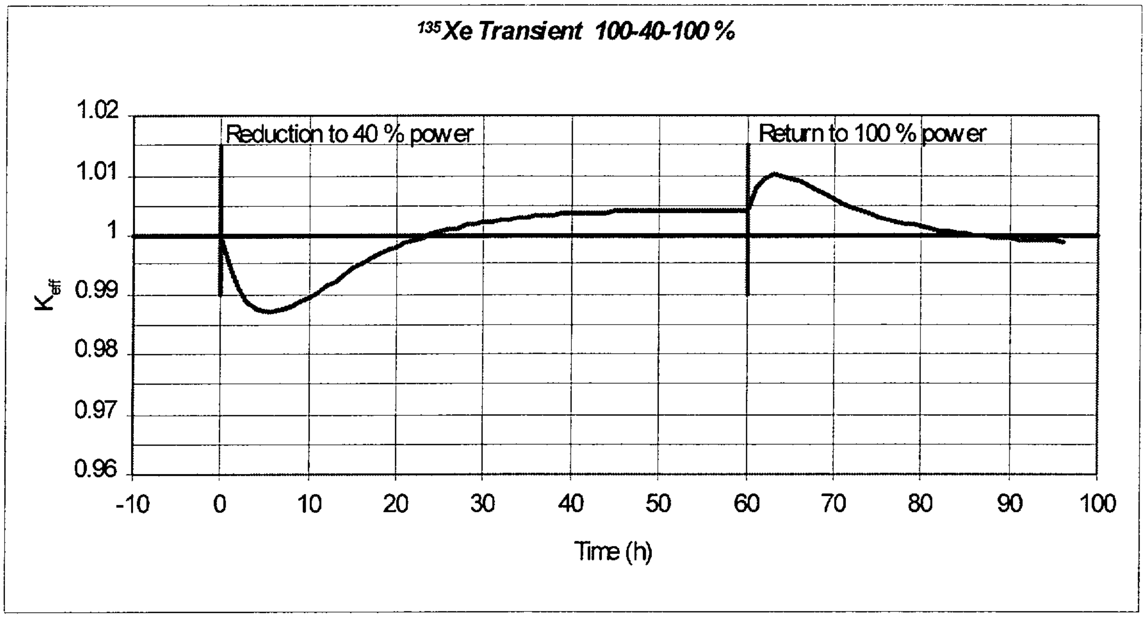


Figure 2.7-3: XENON TRANSIENT

The calculation of control rod reactivity worth is difficult and PBMR places big emphasis on proper validation of the results. The PBMR project is presently using the ASTRA facility in Russia to validate calculational results. The facility's quality control program has been updated and validation results have been quite successful. The facility will also be used to evaluate the effect of a skewed mixing zone.

3. HEAT REMOVAL

3.1 General

The PBMR uses active cooling during startup, normal operation, planned shutdown, and maintenance shutdowns. Active cooling is defined, for this purpose as a pumped loop with an interface heat exchanger and rejection of heat to the sea or in forced draught cooling towers to atmosphere as a back-up system.

The Ultimate Heat Sink (UHS) for the PBMR is the atmosphere. Rejection of heat to the UHS in accident conditions is described below. Heat rejection under normal operating conditions is to the sea, for the demonstration plant, or to the nearby cooling water body for follow-on units.

3.2 Normal Operation

The Active Cooling System (ACS) is coupled to the secondary side of the intercooler and pre-cooler, as shown in ***Figure 2.2-1***. The RUCS, which consists of the RPVCS and the CCS, is also served by the ACS. The RUCS was discussed in ***Section 2.2***. In the startup mode, the reactor is cooled by the SBS. The SBS is used until the Brayton cycle, with its turbo machines, bootstraps. The SBS is electrically driven. It can operate up to 20 percent reactor power and an average core temperature of 750 – 900 °C. Heat removal is via the pre- and inter-coolers. Heat removal is regulated by blower speed and bypass valve manipulation. The bypass valves serve to bypass the turbo machines.

The Brayton cycle removes heat by cycling the helium through the core and the PCU. The heat removed is proportional to the helium inventory. The reactor power will adjust to the amount of the helium inventory. Below 40 percent of full power, control will be by opening the compressor bypass valves.

3.3 Shutdowns

For planned shutdowns, reducing the helium inventory decreases fluidic power. The reactor is shut down and separated from the grid. Opening the bypass valves collapses the Brayton cycle. The SBS is activated to remove decay heat via the active system.

On a scram, opening the bypass valves collapses the Brayton cycle. On load rejection, the generator bypass valves prevent overspeed, the reactor is run back, and the helium inventory is reduced. Within a few minutes, the SBS is started for continued active heat removal.

During a maintenance outage, heat removal is transferred to the RUCS at a convenient point. Primary system pressure is reduced to atmospheric in order to open the remainder of the PCU for maintenance. Shutoff valves at the entrance to the high-pressure turbo compressor and the coolant return lines (referred to as maintenance valves) are used to isolate the RPV from the remainder of the PCU. Thereby, the core is physically separated from the systems to be maintained.

The RUCS is a cooling system with a limited water inventory. If water should leak into the helium coolant during maintenance the volume is small and the consequences will be insignificant. The system is capable of, and will be used to, cooling the core to temperatures needed during maintenance operations.

3.4 Reactor Cavity Cooling System

The RPV cooling under normal operation and accident conditions in which the PCU active cooling system may not be available is via conduction, convection, and thermal radiation through the vessel wall to the RCCS. The RCCS consists of 45 tanks arrayed around the perimeter of the reactor cavity as shown in ***Figure 3.4-1***. The system is operated as three separate loops of 15 tanks each.

In its active mode, coolant from each loop is pumped and rejects heat, via heat exchangers, to the sea. If that heat rejection path fails, then heat is rejected to a cooling tower on the roof of the building. (Failing that, the system would operate in its passive mode, as described below). Anti-syphoning devices are used, as shown in ***Figure 3.4-1***, and no pipes enter the tanks other than at the top, thereby avoiding loss of coolant. Each loop can remove 50 percent of decay heat, providing redundancy in the system.

There is some heat loss through the RPV during normal operations. That heat is also removed via the RCCS. Without the Brayton cycle, SBS, or RUCS, all cooling is provided by the RCCS.

Arrangement of Pipes and Headers

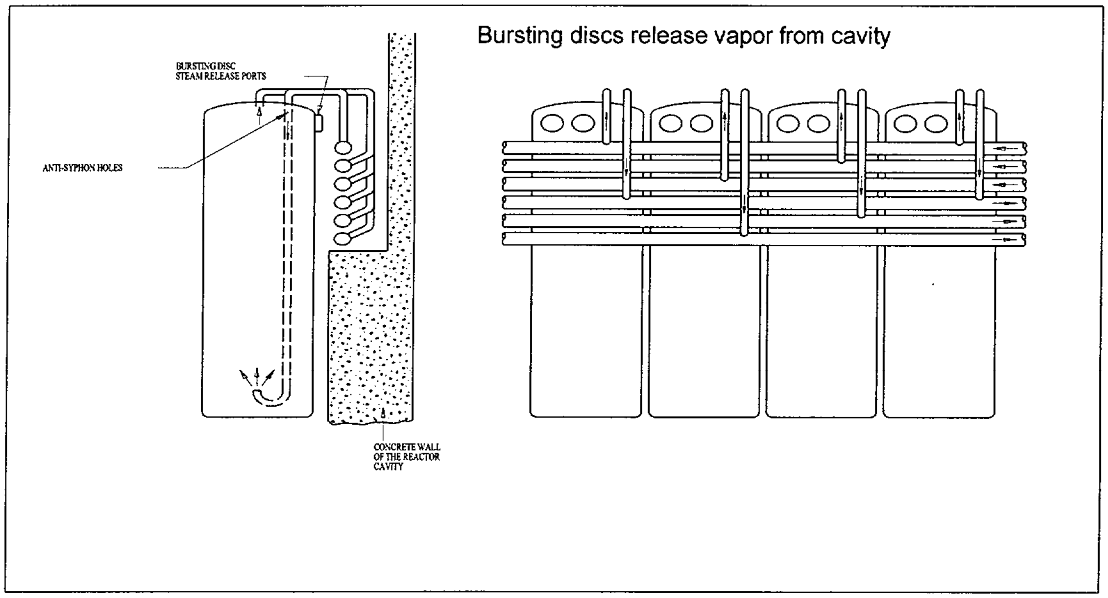


Figure 3.4-1: ARRANGEMENT OF PIPES AND HEADERS

If the active system removing heat from the RCCS fails, the system goes into its passive mode. Temperatures in the tanks will increase until boiling begins. Subsequent increases in pressure in the tanks will result in bursting of rupture discs, as shown in ***Figure 3.4-1***. Water vapour from subsequent boiling is released directly to the atmosphere (UHS). There is sufficient water inventory in the RCCS tanks to remove decay heat for five days in this mode. Tank level is monitored as part of the post-event monitoring system. The RPV and core barrel temperatures remain within Code Case limits during such an event. There is no need for immediate operator actions to assure core cooling.

3.5 Water and Air Ingress

Ingress of water and air into the core poses operational and potential safety concerns. The potential for water ingress is minimized by design. The water/gas interface during normal operations is the heat exchangers in the pre- and inter-cooler. There is a large pressure difference, with the helium pressure significantly exceeding the water pressure. This will prevent water ingress in the event of any leaks in the heat exchanger, reducing the probability of water ingress to near zero.

Cooling of an isolated RPV with the RUCS involves pressures on either side of the heat exchanger boundary that are approximately equal. Water ingress is possible in the event of leaks in this heat exchanger. Gross in-leakage would not be expected, since there is no pressure differential providing a significant driving head. The total water inventory of the RUCS is nevertheless kept small, to minimize the consequences (e.g., corrosion and reactivity) from water ingress.

The ingress of air into the reactor is a hypothetical event associated with a Depressurized Loss of Forced Cooling (DLOFC) event. The confinement construction is such that the amount of oxygen available in the event of a DLOFC is limited. A chimney effect, admitting air into the primary coolant boundary, is only possible if there are two openings into the primary circuit one at the bottom and one at the top an unlikely scenario. It is possible for some air to enter the system via stratified flow in a single opening, allowing both outflow of helium and inflow of air. Such situations have not yet been analyzed in any detail.

3.6 Analyses of Heat Removal Capabilities

Temperature calculations have been performed using a neutronics code coupled to a heat transport code (TINTE and VSOP coupled to Thermix and STAR-CD). The calculations evaluate the time-dependent heat-up of the fuel and core components. Calculations were performed assuming RCCS is at a constant 60 °C, consistent with its operation in active cooling mode.

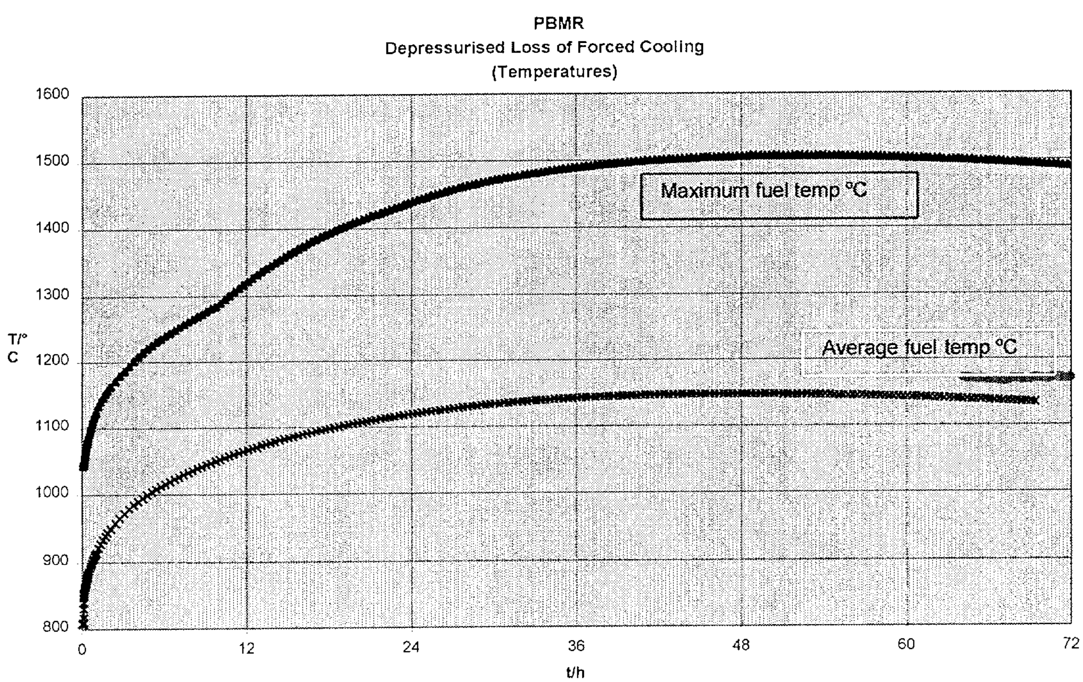


Figure 3.6-1: DEPRESSURIZED LOSS OF FORCED COOLING (TEMPERATURES)

Figure 3.6-1 shows the analytical results for a DLOFC. Average and maximum fuel temperatures are displayed. Maximum temperature peaks at 1500 °C. This calculation was performed both with control rods in and out. There is no distinguishable difference in the maximum or average temperat ures, attributable to the strong negative temperature coefficient of the reactor.

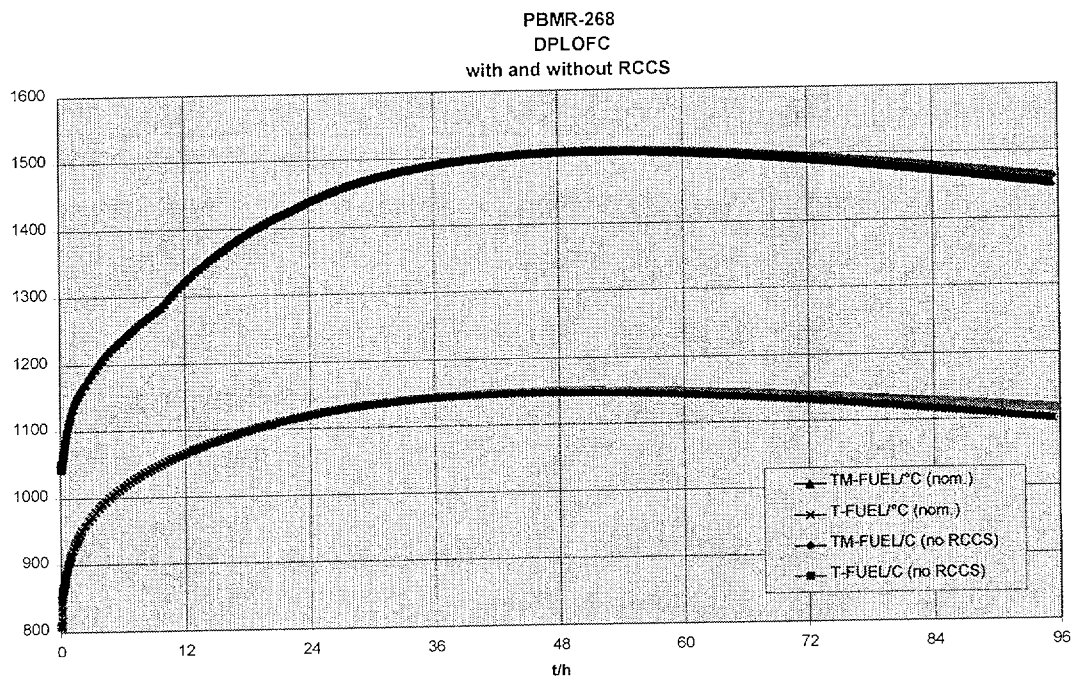
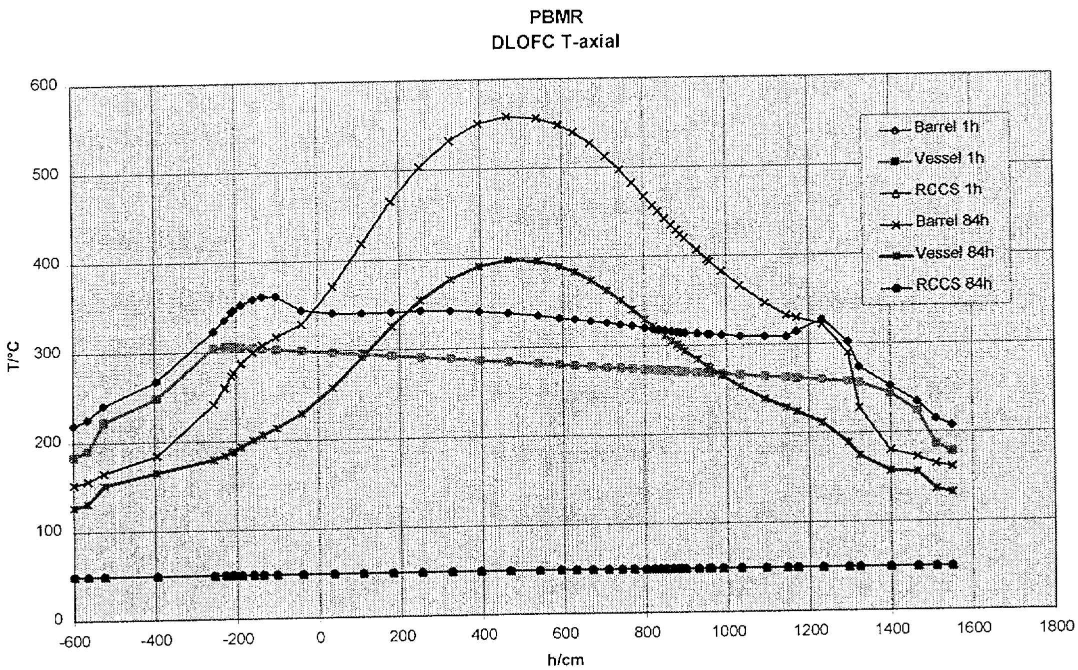


Figure 3.6-2: DLOFC WITH AND WITHOUT RCCS

Figure 3.6-2 shows the effect of RCCS. Maximum and average fuel temperatures are displayed for the same event (DLOFC) with and without operation of the RCCS. (The latter case essentially assumes the RCCS tanks are dry in the time of the event). The difference in fuel temperature is very small. The heat sink in the no-RCCS case is the reactor cavity concrete.



Bottom of core Top of core

Figure 3.6-3: DLOFC T-AXIAL

Figure 3.6-3 presents two sets of curves: one for one hour after a depressurized loss of forced cooling, and a second for 84 hours after the event. At 84 hours, the core barrel reaches 540 °C. For type 316 stainless steel, ASME Code Case N-201-4 makes allowance for 1500 °F (815.6 °C) for certain levels of stress that envelope the PBMR conditions for the core barrel. ASME code case N-499-1 for SA 508 class 3 forgings allows a maximum temperature of 1000 °F (537 .8 °C) for the RPV and temperatures and pressures that envelope the PBMR conditions. It should however be noted that the code case allows a maximum of 1000 hours at temperatures between 800 °F and 1000 °F and permits only 3 excursions above 800 °F.

[**PROPRIETARY** – Figure intentionally removed]

Figure 3.6-4: RPV AND REACTOR CAVITY STRUCTURES

[**PROPRIETARY** – Figure intentionally removed]

Figure 3.6-5: MESH USED IN ANALYSIS

Figure 3.6-5 [**PROPRIETARY** – Figure notes intentionally removed]

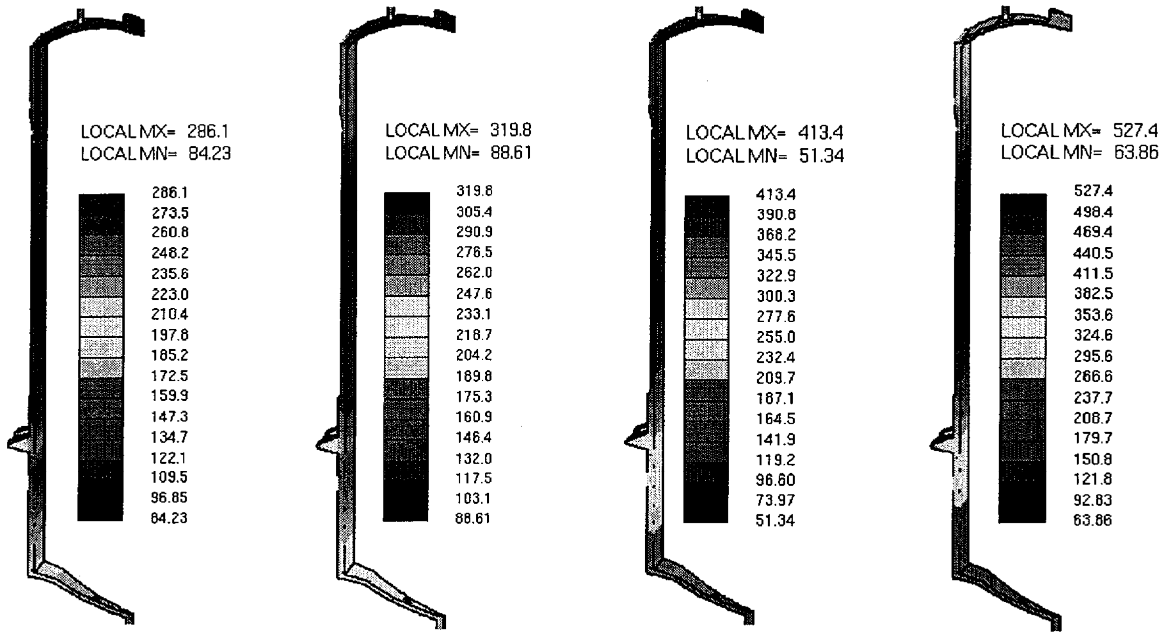
[**PROPRIETARY** – Figure intentionally removed]

Figure 3.6-6: REACTOR TEMPERATURE DISTRIBUTION PLOFC [**PROPRIETARY** – Pressure intentionally removed]

[**PROPRIETARY** – Figure intentionally removed]

Figure 3.6-7: REACTOR TEMPERATURE DISTRIBUTION DLOFC [**PROPRIETARY** – Pressure intentionally removed]

RPV Temperatures



100% MCR | 40% MCR | PLOFC | DLOFC

Figure 3.6-8: RPV TEMPERATURES

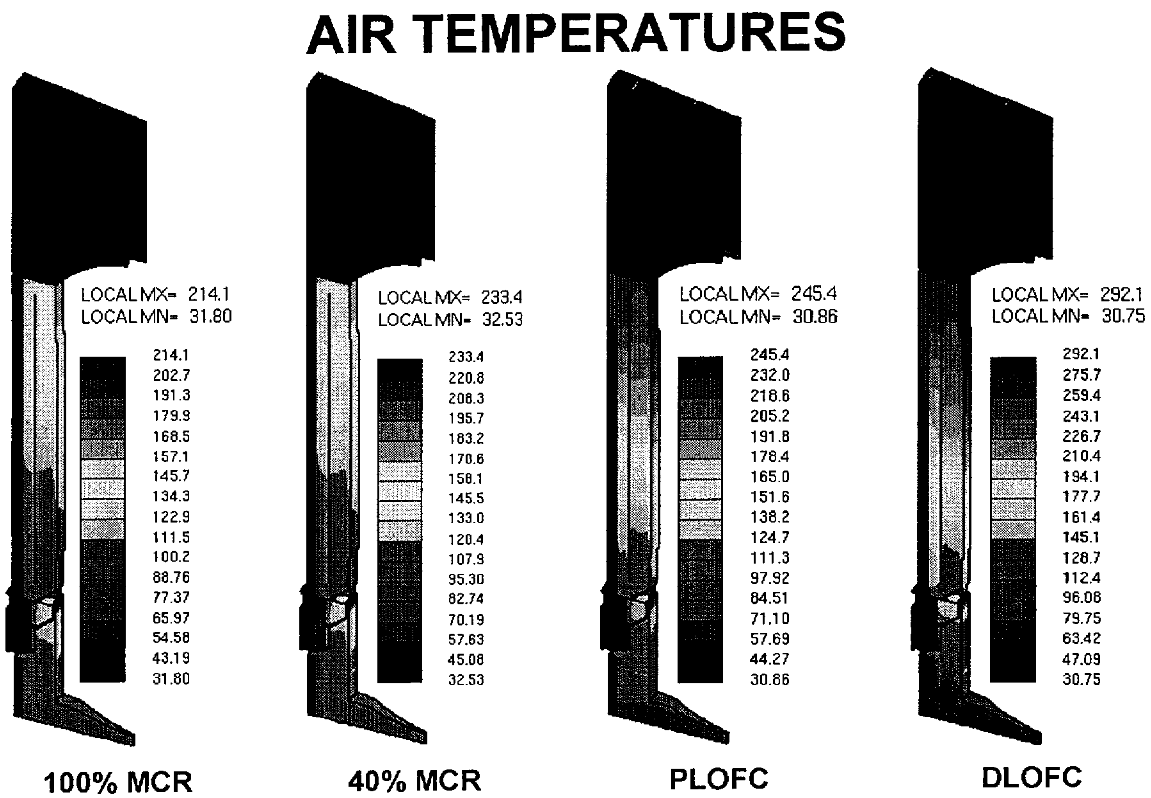


Figure 3.6-9: AIR TEMPERATURES

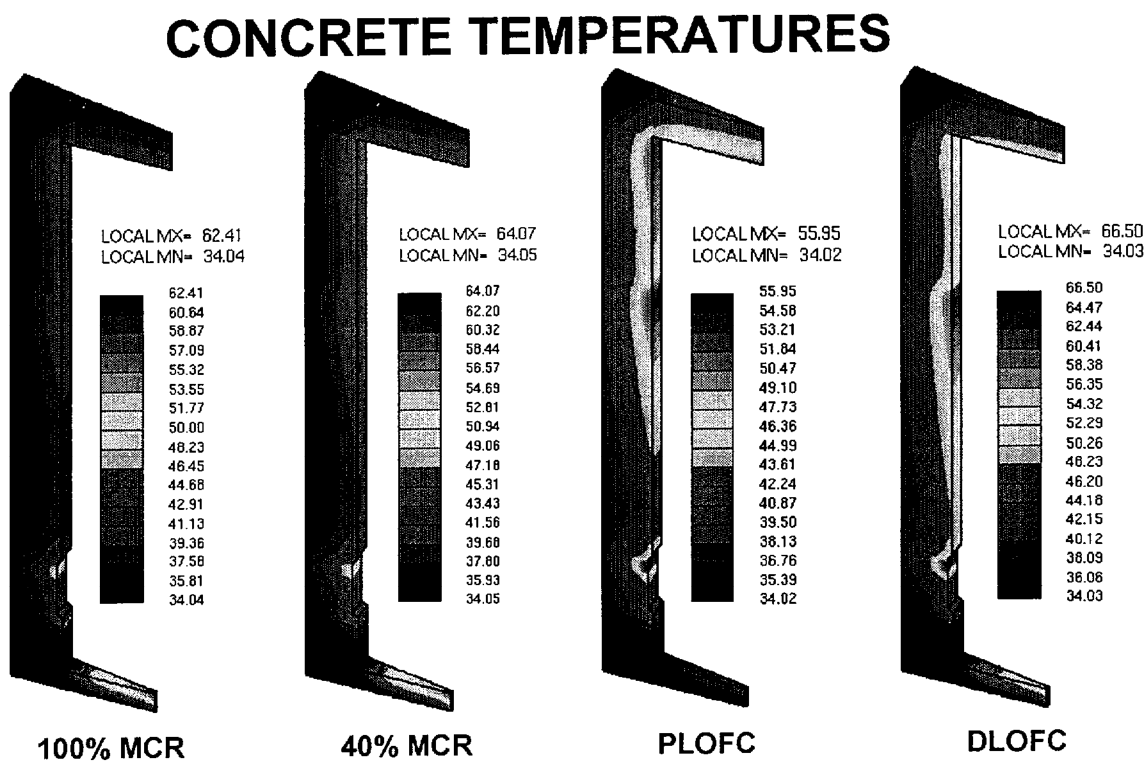


Figure 3.6-10: CONCRETE TEMPERATURES

Attachment 5

-- Non-Proprietary Version –

"PBMR Core Design" Presentation

Dated August 16 2001

29 pages

Submitted March 4, 2002

P B M R

PBMR CORE DESIGN

Johan Slabber, Ph.D.
PBMR, Pty
16 August 2001

Objective

- Inform and educate NRC regarding key safety design features
- Describe application of analytical codes used by PBMR Pty.
- Reach agreement on what constitutes sufficient design information and analytical methodologies to support a US license application

Topics

- Physical Layout
- Pebble Flow Overview
- Core Calculations
- Conclusions

Introduction

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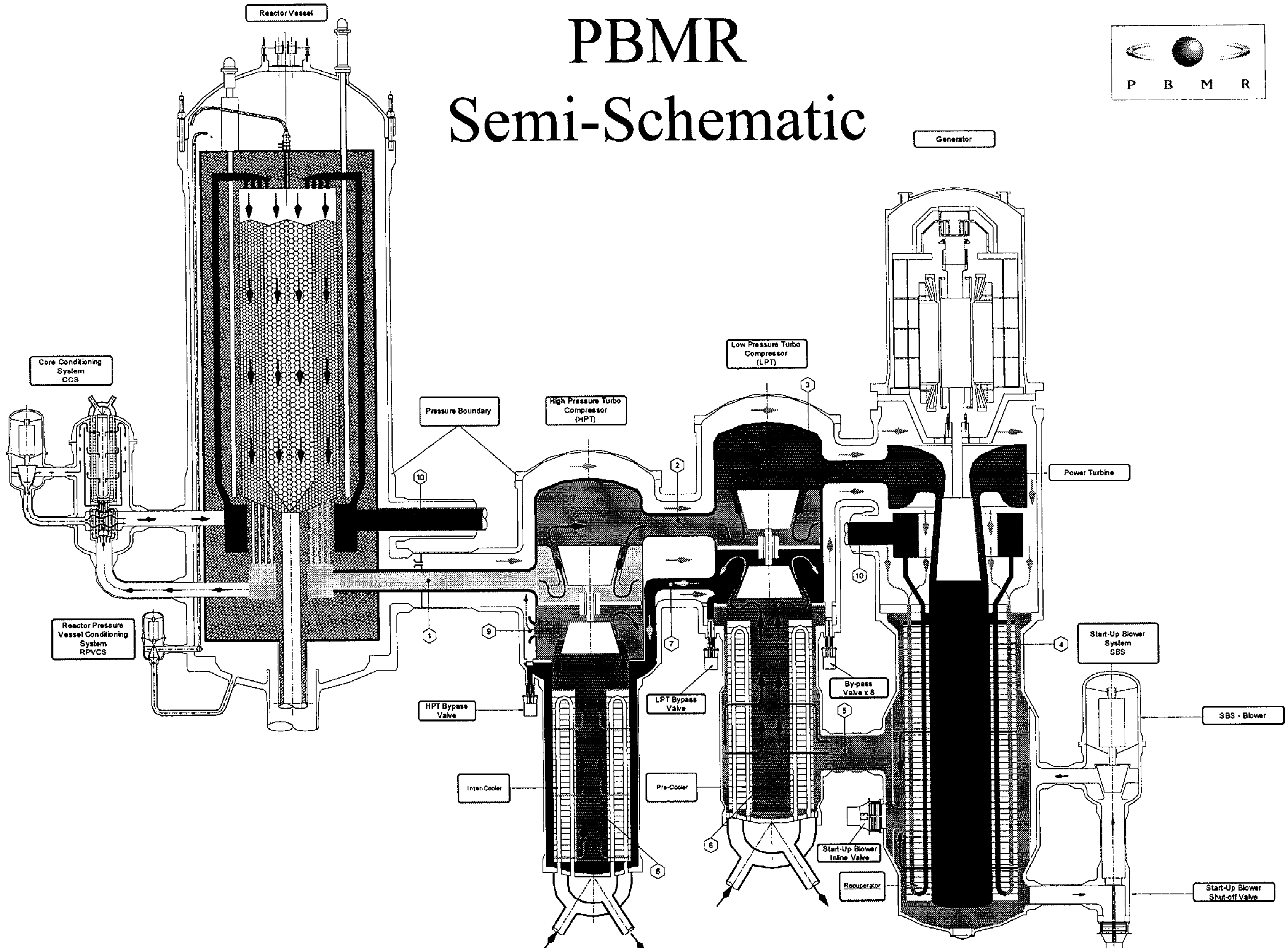
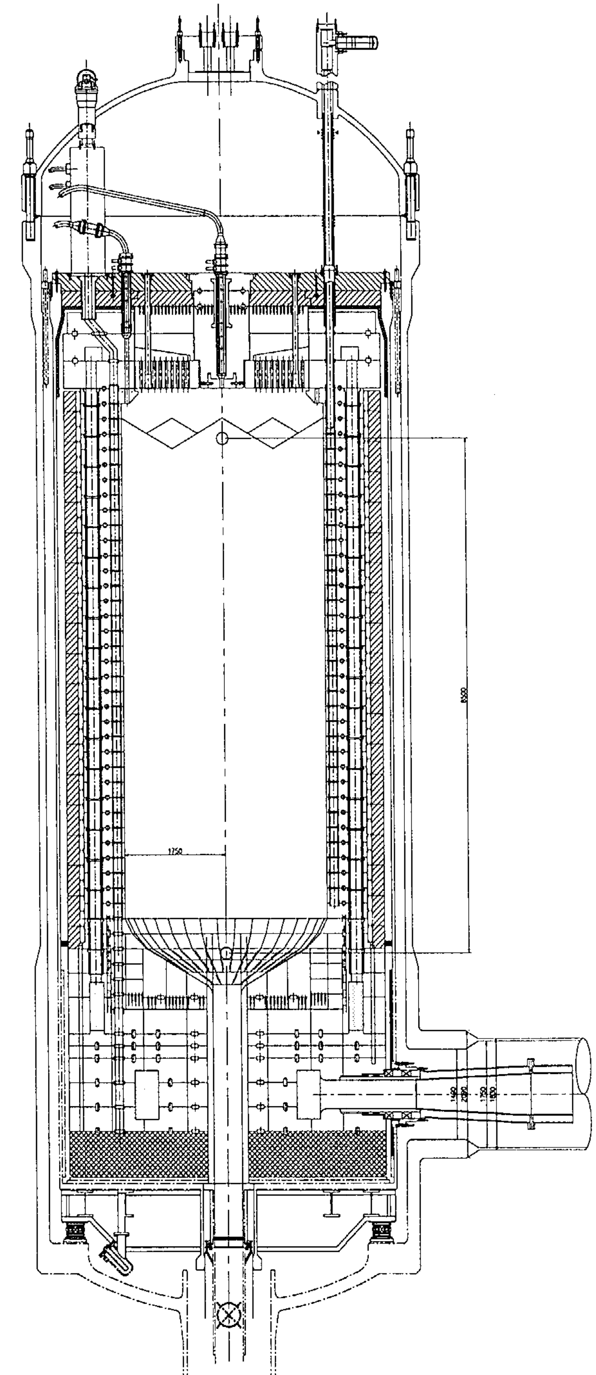
- Safety characteristics as basis for design
- HTR-MODUL Reactor Unit (RU) design as reference
  - Control elements in reflector only
  - H/D ratio increased 1:1 to 3:1
- Introduction of "graphite column" as central reflector

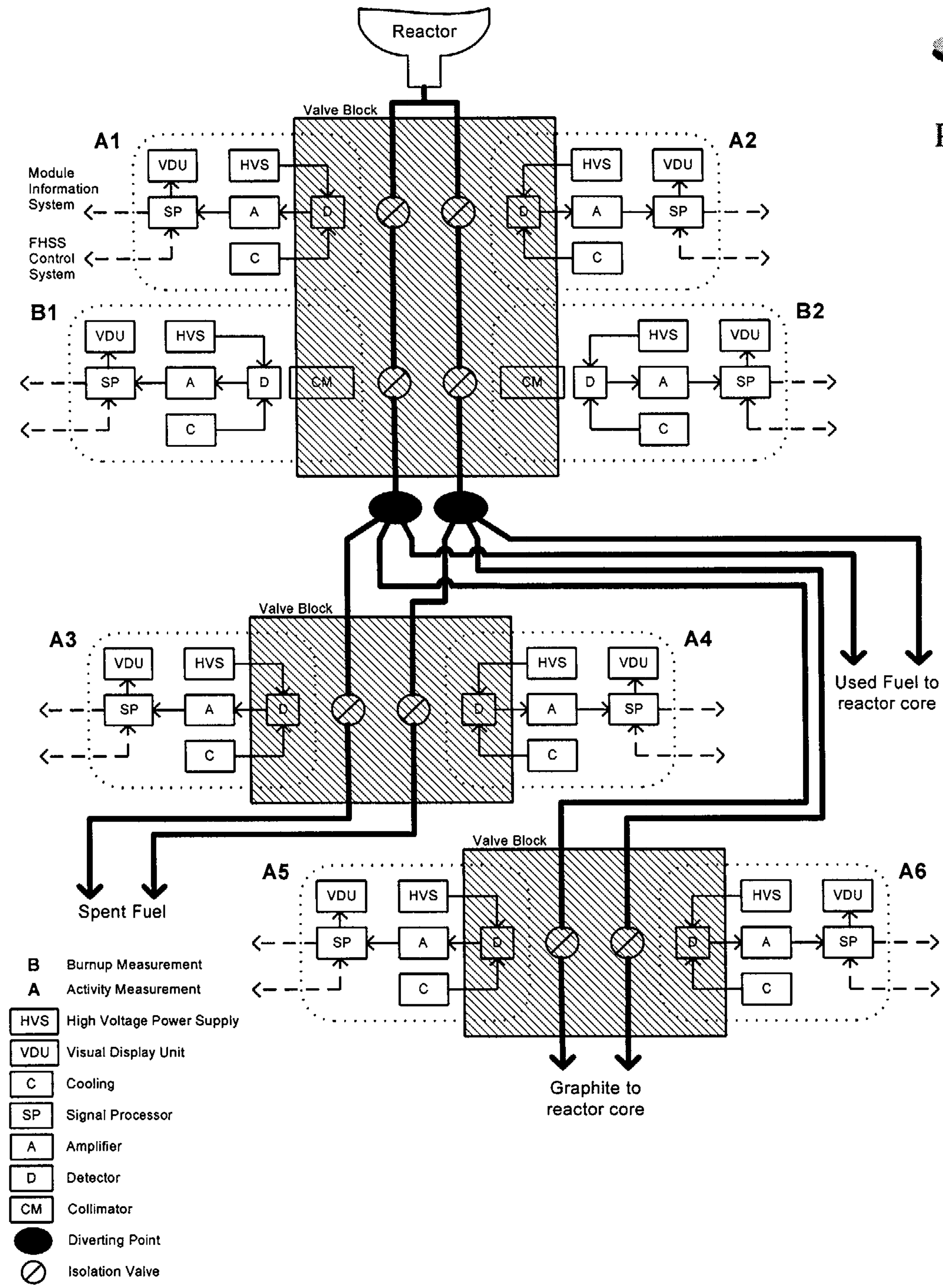
PBMR
Semi-Schematic



PBMR RPV Layout



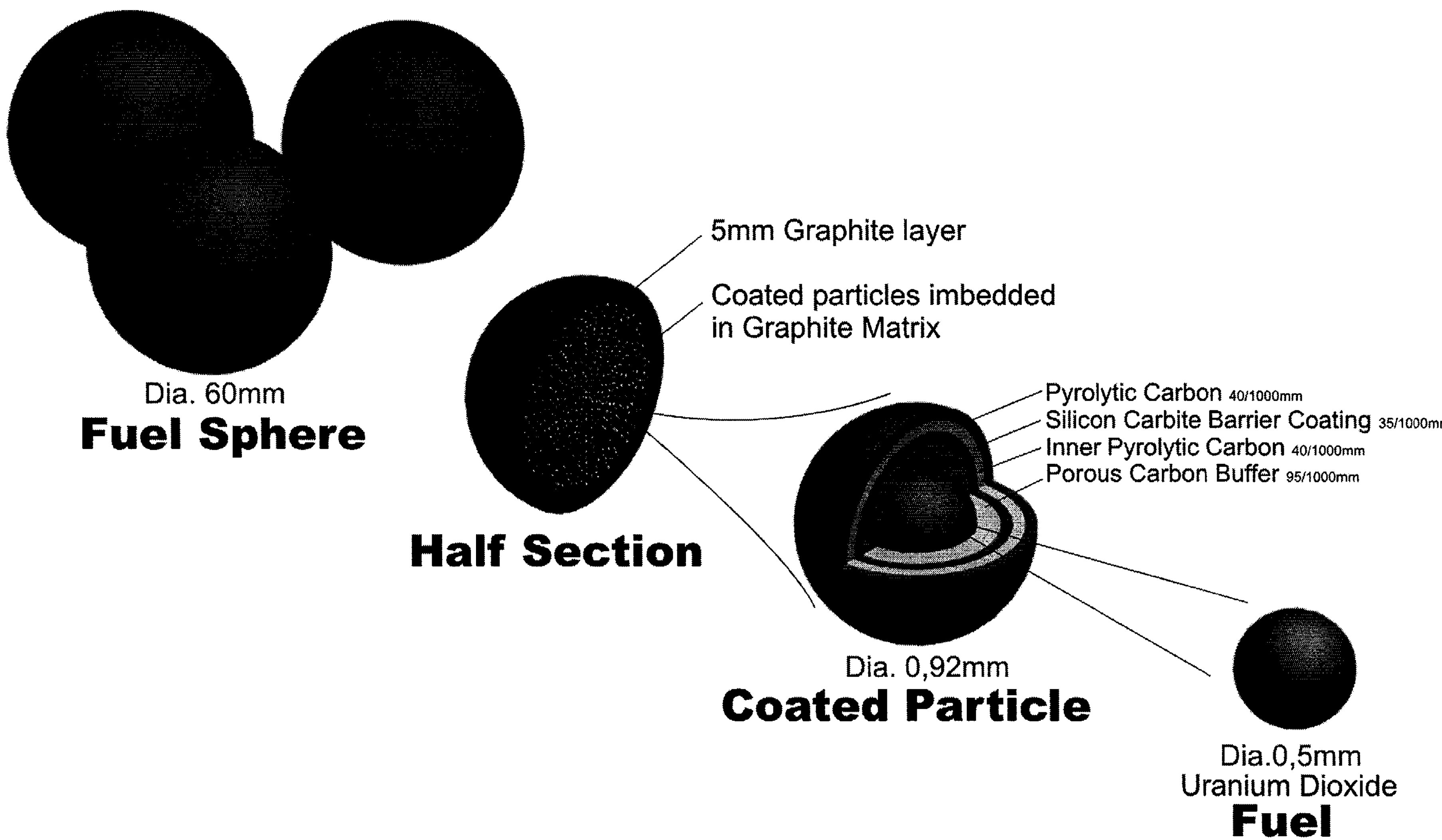
PBMR FHSS Schematic



P B M R

Aug 01

Fuel Sphere Design



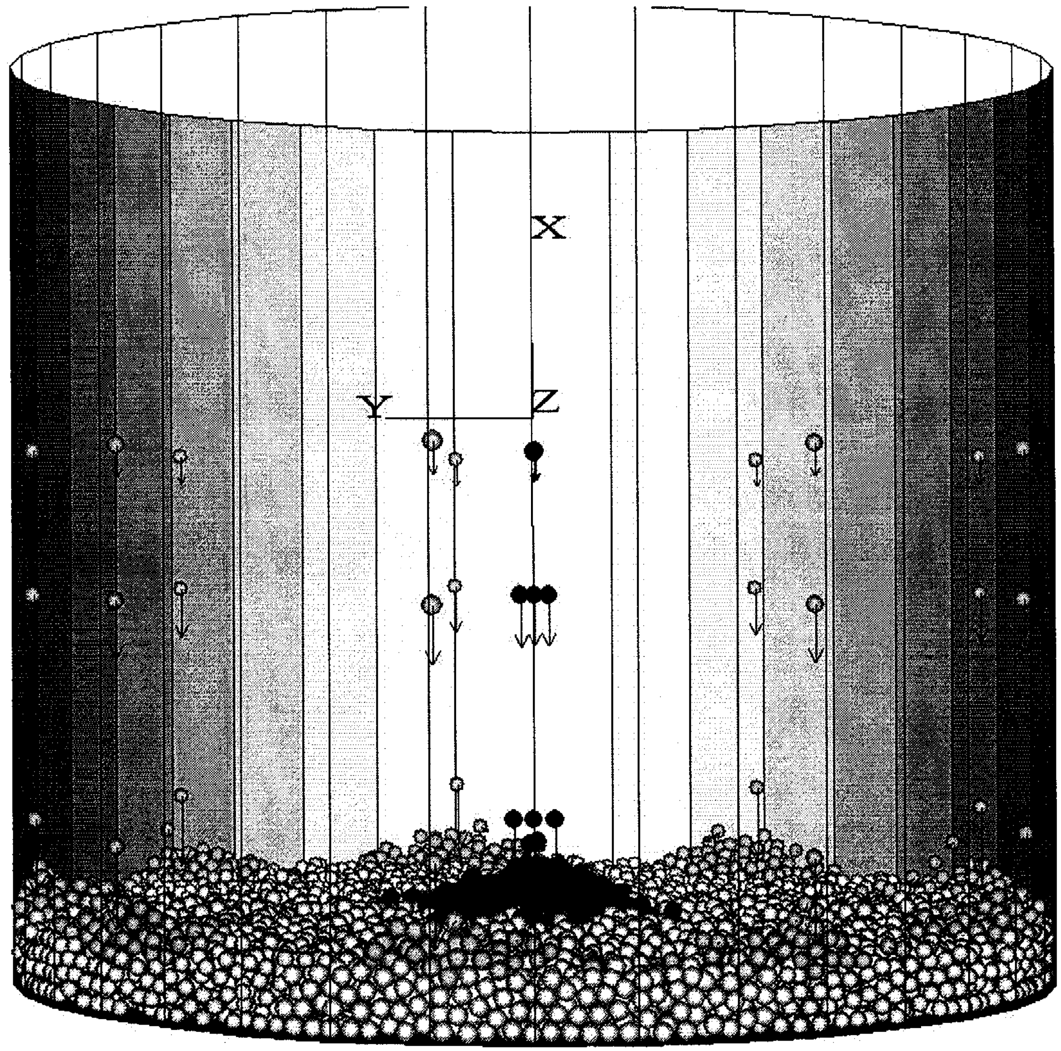
Geometry

- Pebble Flow Experiments
  - R&D Final Report by Siemens
- Computer Simulation
  - Model development at FZJ
- Select Benchmark Experiment
  - Compare experiment and computer model
- Verify VSOP pebble flow model

PFC-3D code

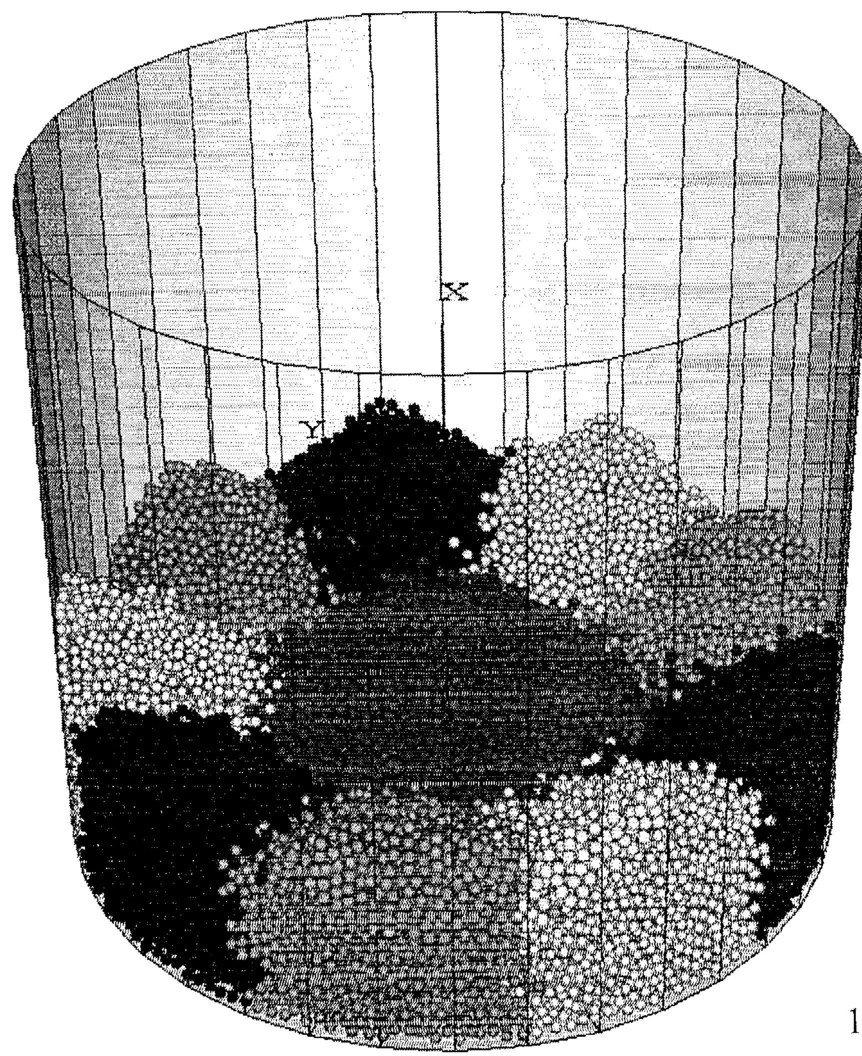
- The PFC^{3D} code used for PBMR analysis is divided into two parts:
  - Analysis of the top of the core in a cylindrical vessel
  - Analysis of the pebble flow through the core

Filling the Vessel

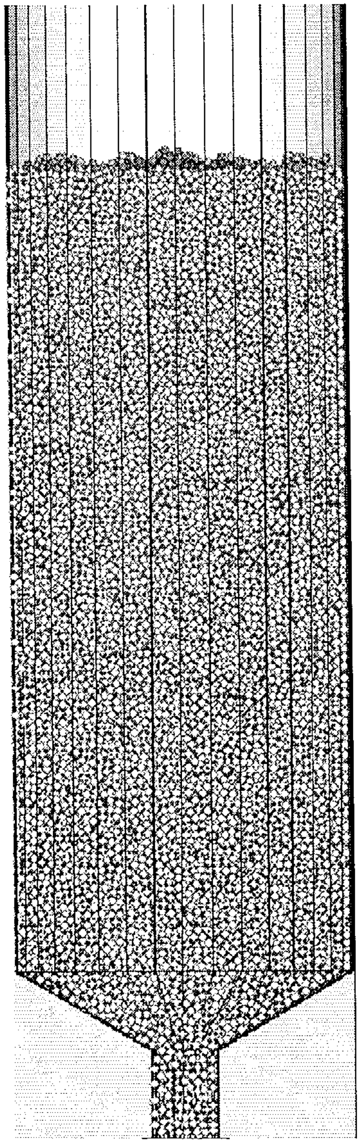


Core Sphere Flow Analysis

Detailed analysis of the dynamics of the spheres in the upper core volume are completed. The behavior of the spheres in this region determines the formation of the two zone core with a mixing zone.



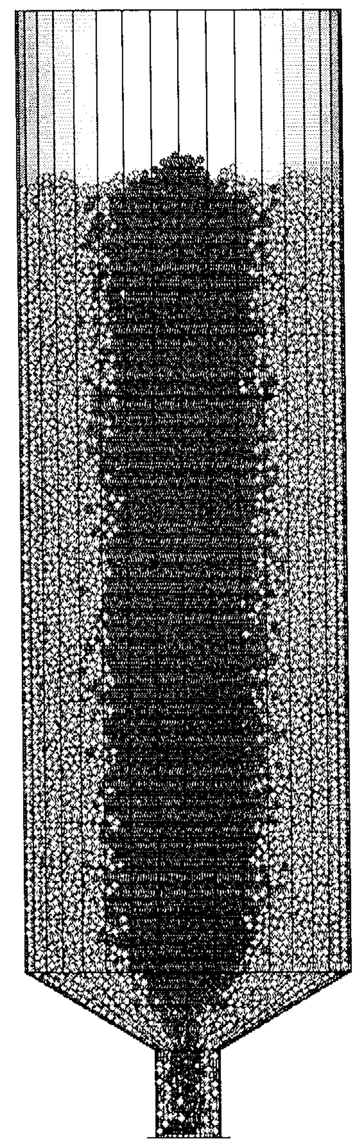
Core Sphere Flow



The motion of the fuel and graphite spheres in the PBMR core is an important area of study. Large scale simulations using the Discrete element modeling technique have been carried out.

The picture on the right shows simulation results for the core simulation, these results show a clearly defined three zone core.

A validation exercise has been undertaken. Agreement between the PFC-3D simulations and the ANNABEK experiment was within 10%.

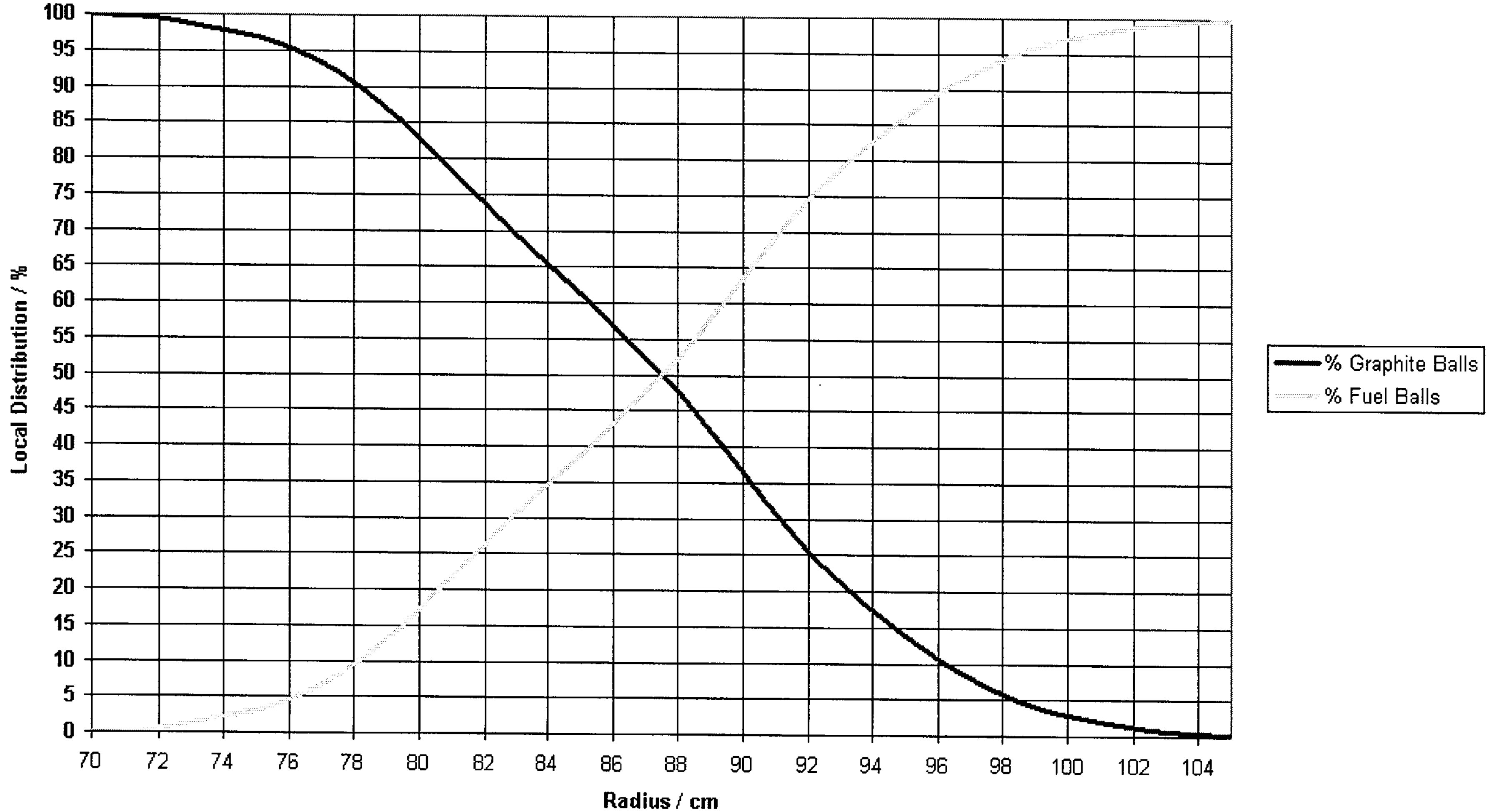


Proprietary Information Removed

Flow Lines

Local Distribution vs. Core Radius

P B M R



Calculational Approach

- Prepare input models for:
  - Fuel
  - Geometry
  - Pebble flow
  - Core compositions
- Perform equilibrium and/or initial core calculations
- RU status is preserved for later restart

Comments on Pebble Flow Experiments

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1. There is a separation of fuel and graphite spheres
2. The calculated thickness of the mixing-zone is 22cm
3. Graphite / Fuel concentration in mixing zone: 48.5 / 51.5
4. The center of the mixing zone located at the theoretical location of 87.5 cm
5. No single or packages of fuel spheres observed in the graphite area or graphite spheres in the fuel area

Flow of Pebbles

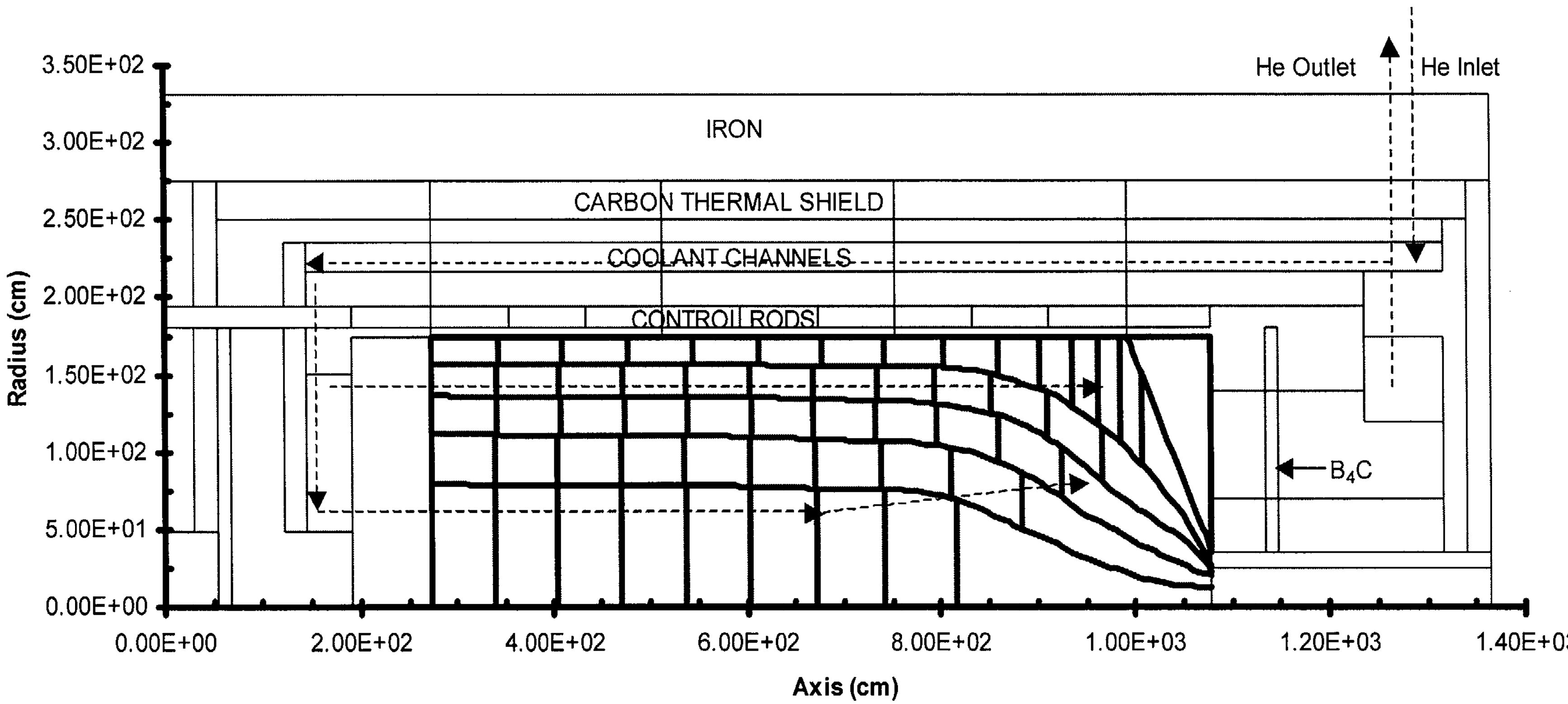
- Model Description:
  - Parallel flow in the upper part of the pebble bed
  - Effect of cone and discharge tube in the bottom region
  - Transition from parallel flow to flow pattern via interpolation

VSOP Implementation

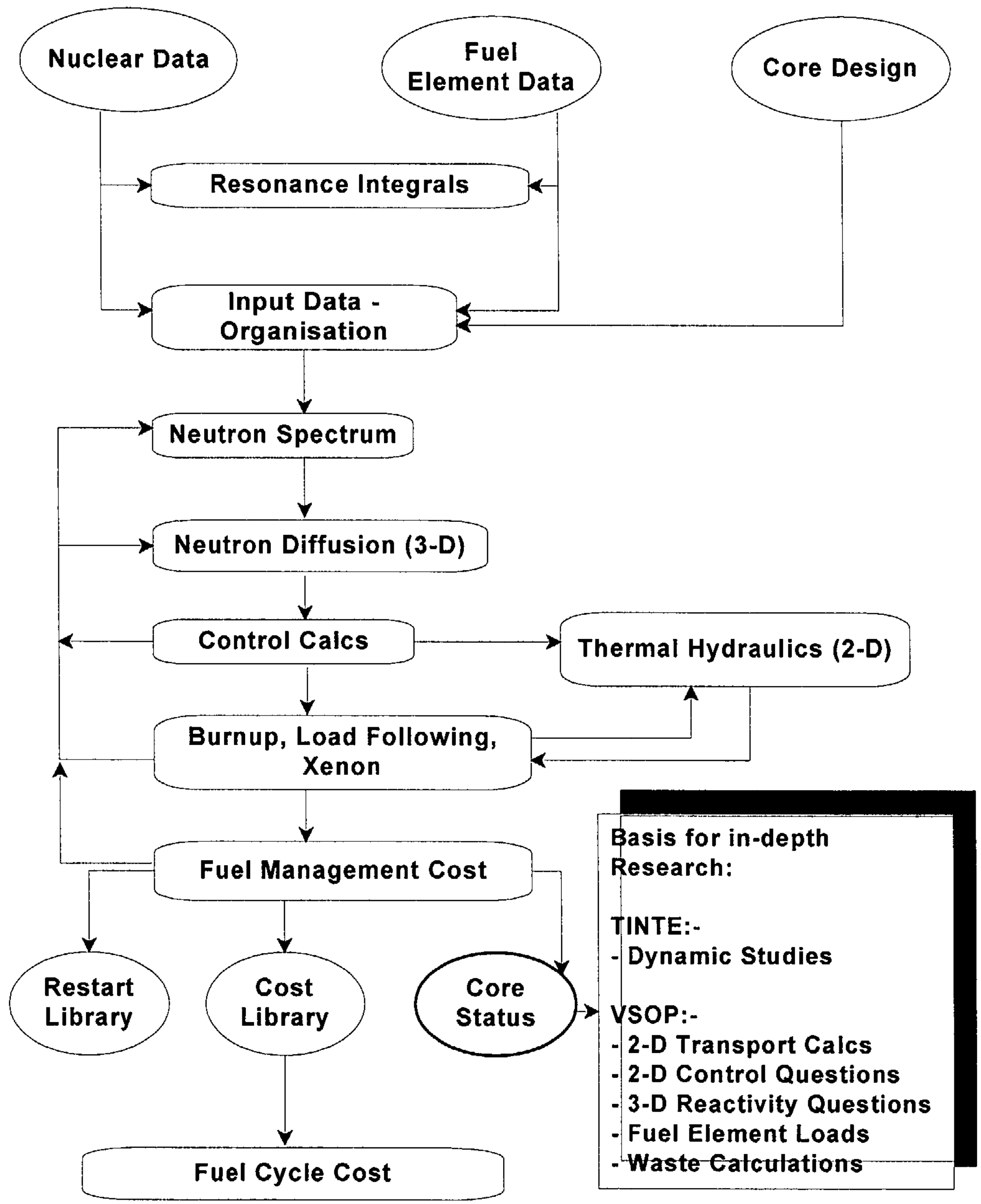
- Ch. 1: 20% of total volume loaded in central column as graphite spheres
- Ch. 2: 20% of total volume loaded as a 50/50 mixture of fuel and graphite spheres
- Ch. 3-5: 20% of total volume in each channel consisting of fuel only
- After discharge considered mixed and reloaded according to the scheme proposed in previous slide

VSOP RU Model

REF-OKT 268 MW_t Layout



Calculational Logic



Temperature Coefficients

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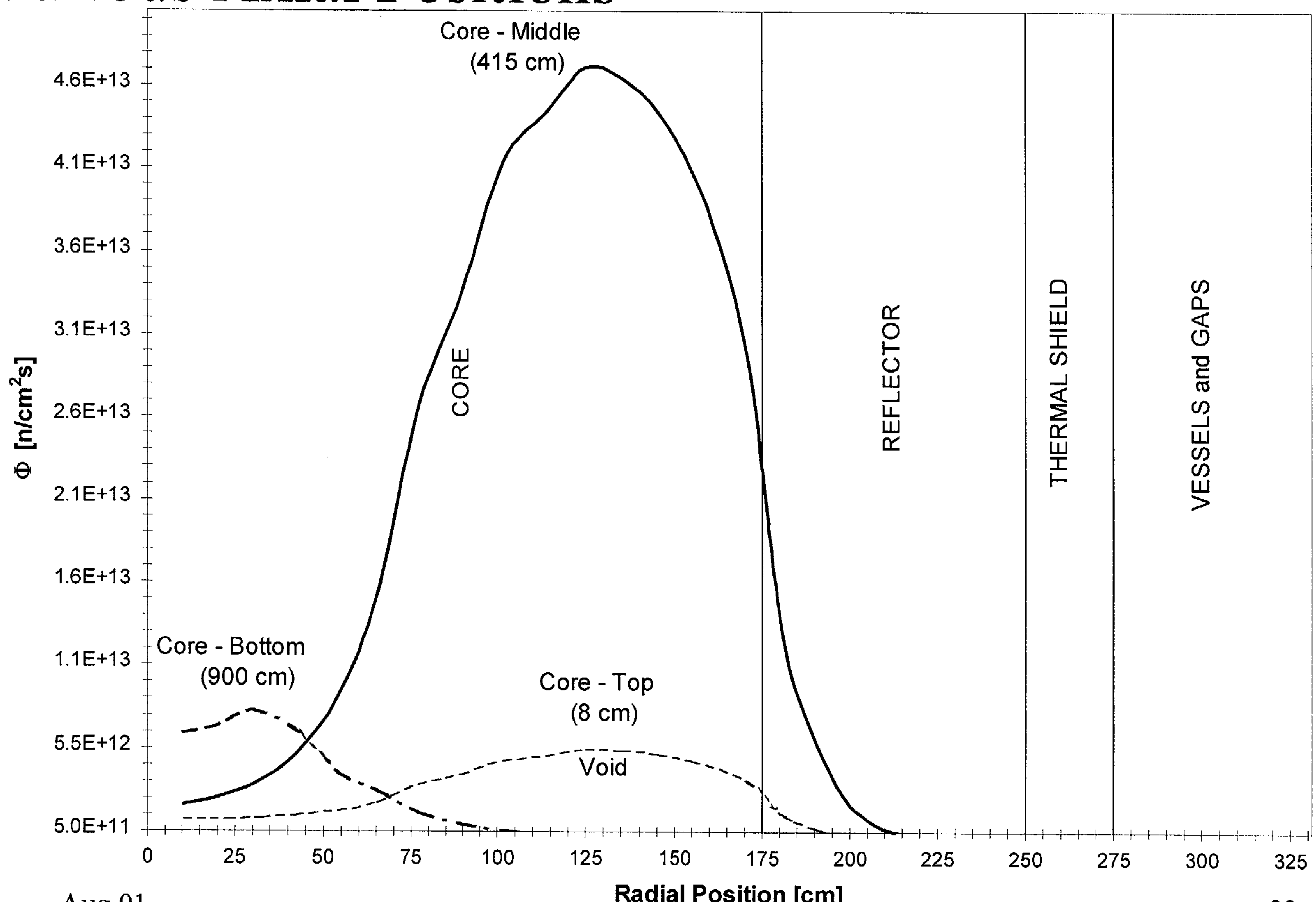
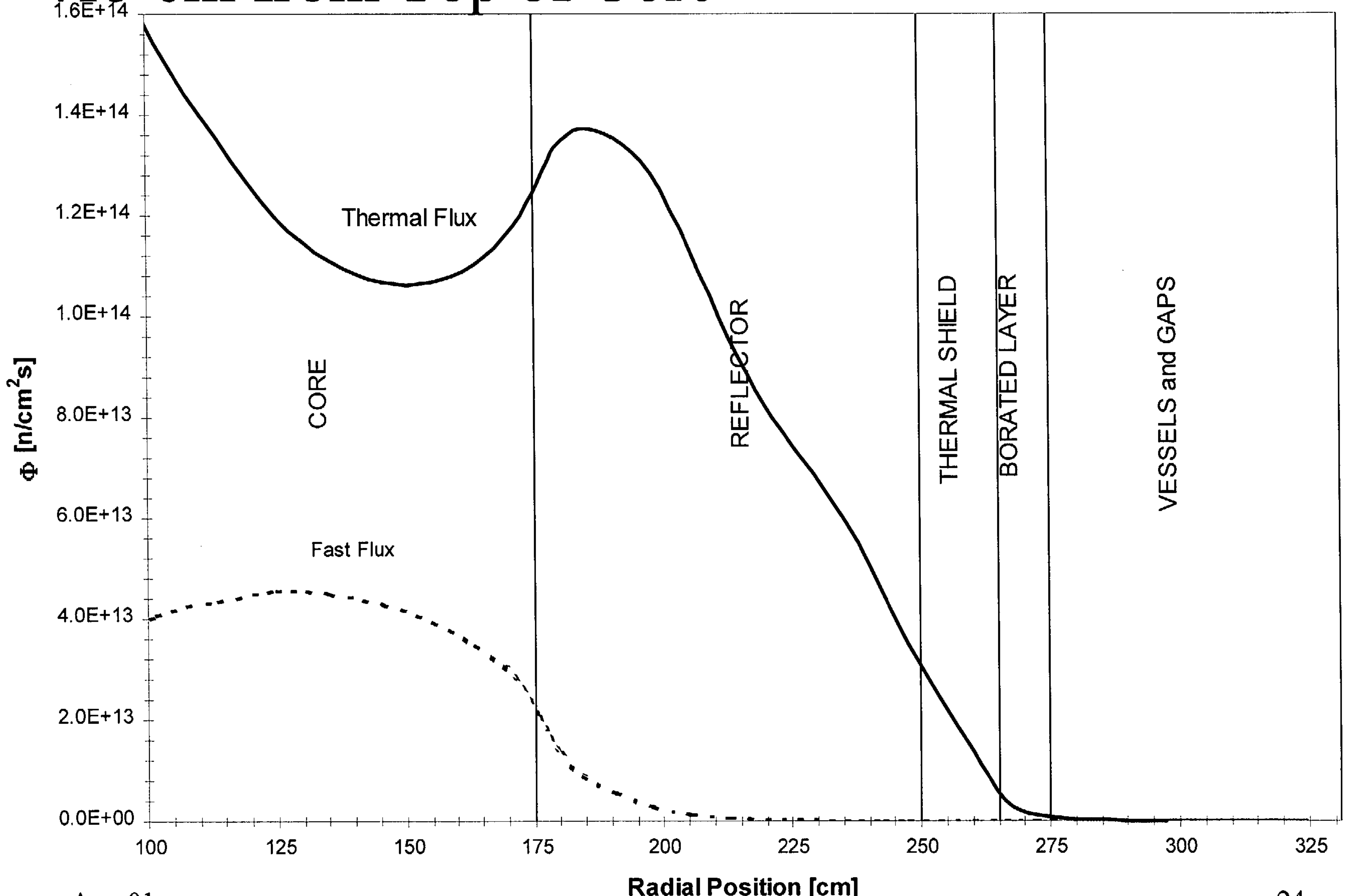
VSOP Option		2-D	3-D
Temperature coefficients at operating conditions: $\Delta k_{eff}/^{o}C \times 10^{-5}$			
Fuel (Doppler coeff. of U-238)		-3.28	-3.25
Moderator in fuel part of the core		-3.30	-3.40
Central graphite zone		+0.93	+0.82
Reflectors		+1.48	+1.40
Total		**-4.17**	**-4.43**

Radial Fast Flux Distribution at Various Axial Positions

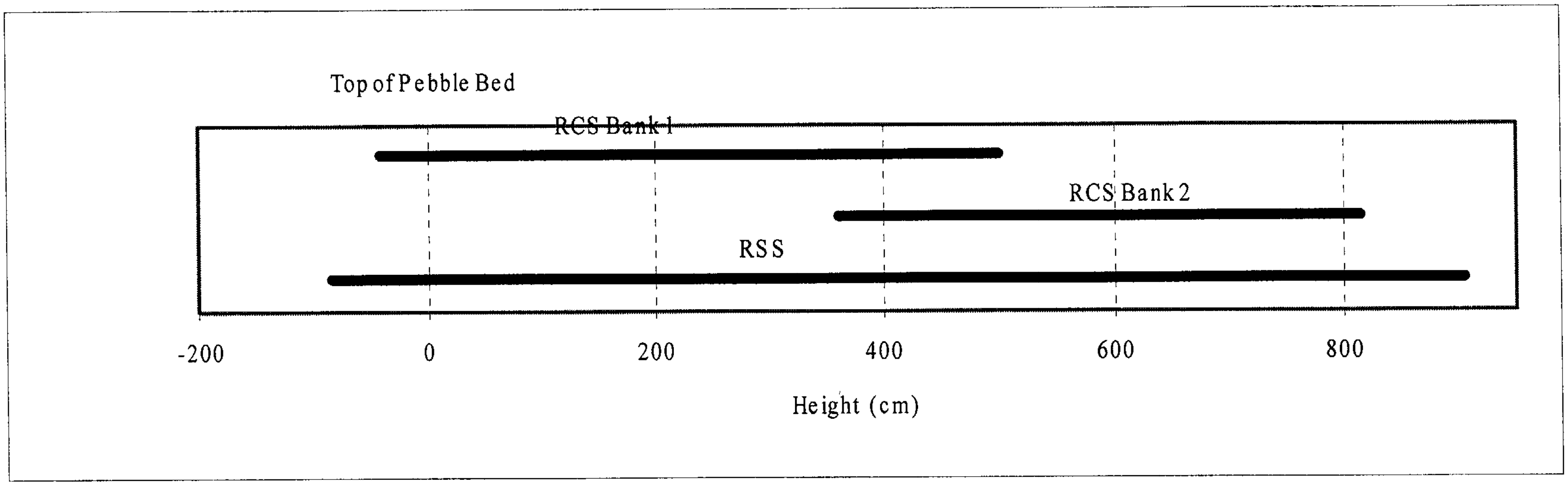


Radial Thermal Flux Distribution at 415 cm from Top of Core

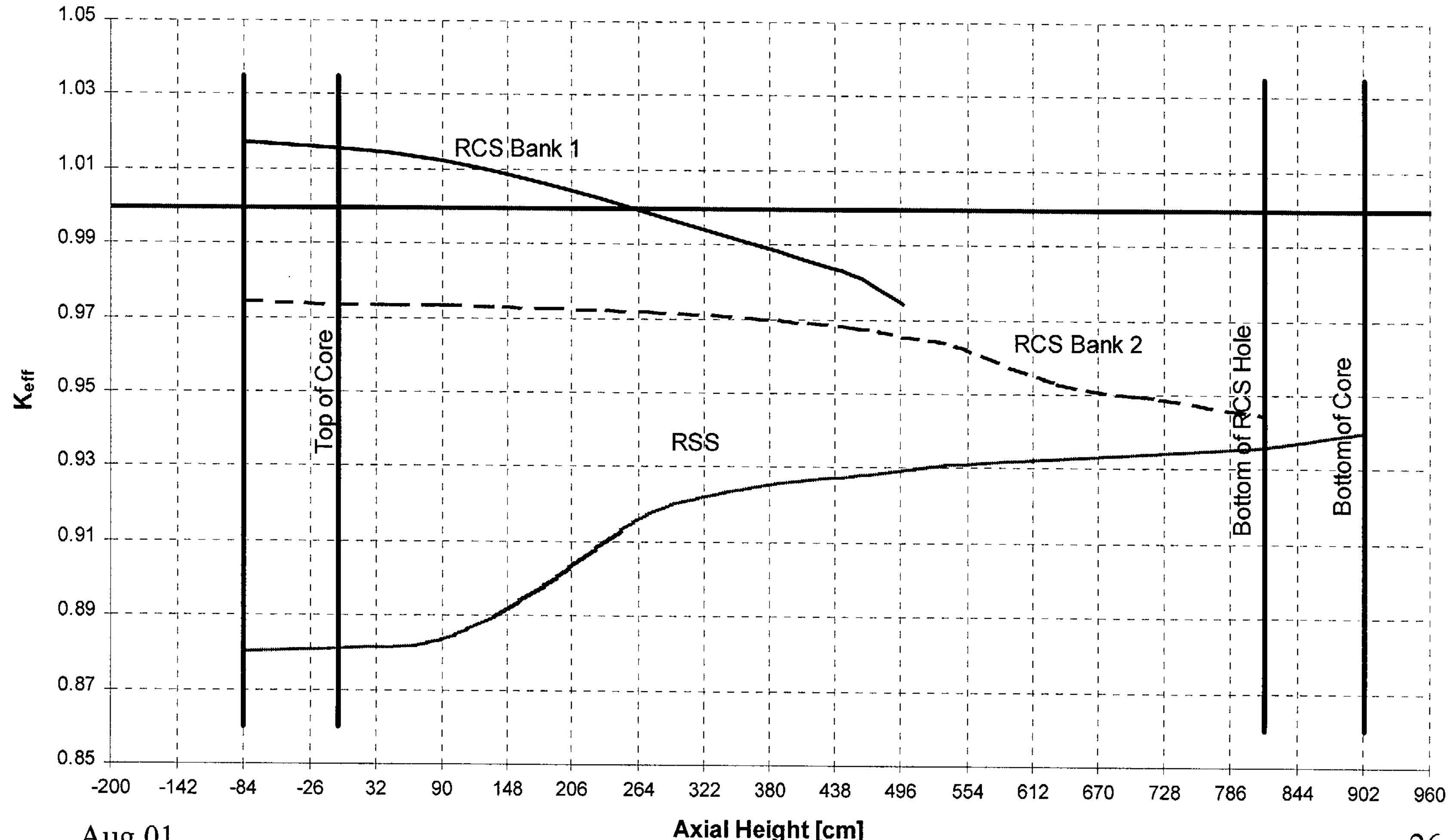


PBMR

RCSS Position: Inserted



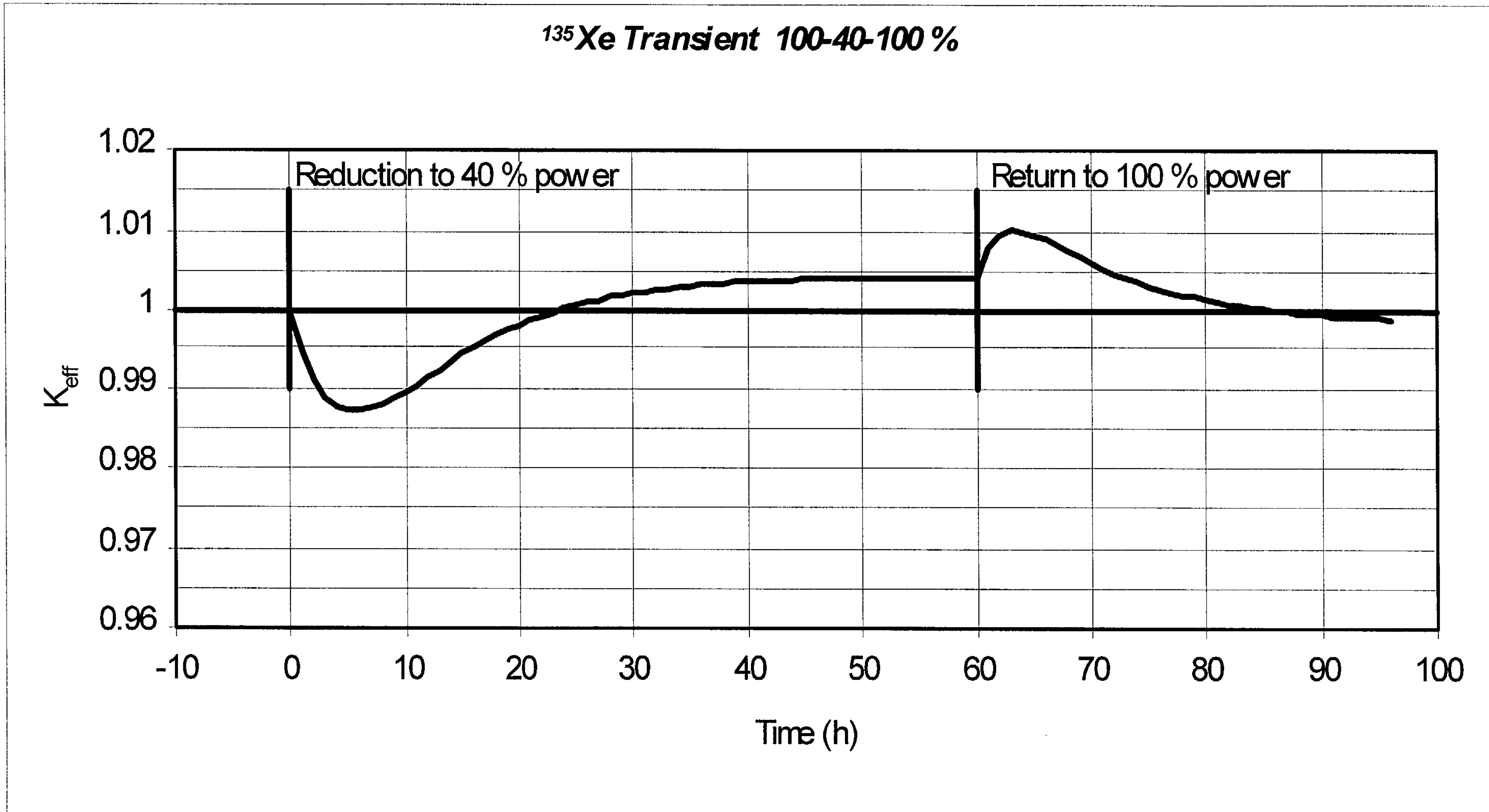
RCSS Characteristics



Reactivity Balance

Requirements: $\Delta K_{eff}/^{o}C$	Value
Operation -> 50 °C	+0.0318
Decay of Xe-135	+0.0490
Decay of other isotopes over 30 days	Neglected conservatively
Xe-override (100-40-100%)	+0.012
Uncertainties	+0.008
TOTAL	+0.101
Capability (9x5.823m top & 9x5.823 bottom): $\Delta K_{eff}/^{o}C$	
9 top RCS in side reflector	-0.0429
9 bottom RCS in reflector	-0.0341
16 RSS in reflector (18 RSS)	-0.0540 (-0.0595)
5% Uncertainty	+0.0066 (+0.0068)
TOTAL	-0.1244 (-0.1297)
Reactivity Shutdown Margin	*-0.0234 (-0.0287)*

Xenon Transient



Benchmarking using PBMR

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- RU operation involves closely associated processes of neutron physics, burnup, heat transfer and fuel handling
- In an existing RU these steps may be monitored and measured
- Facility design, construction, and licensing of a RU are based on repetitive computer simulation to build-up a large database
- Simulation offers insight into physical processes not accessible for experimental investigation

Attachment 6

-- Non-Proprietary Version –

"PBMR Heat Removal" Presentation

Dated August 16 2001

25 pages

Submitted March 4, 2002

P B M R

PBMR HEAT REMOVAL

Johan Slabber
PBMR Pty.

OBJECTIVE

- Inform and educate NRC regarding key safety design features
- Describe application of analytical codes used by PBMR Pty.
- Reach agreement on what constitutes sufficient design information and analytical methodologies to support a US license application

PBMR HEAT REMOVAL

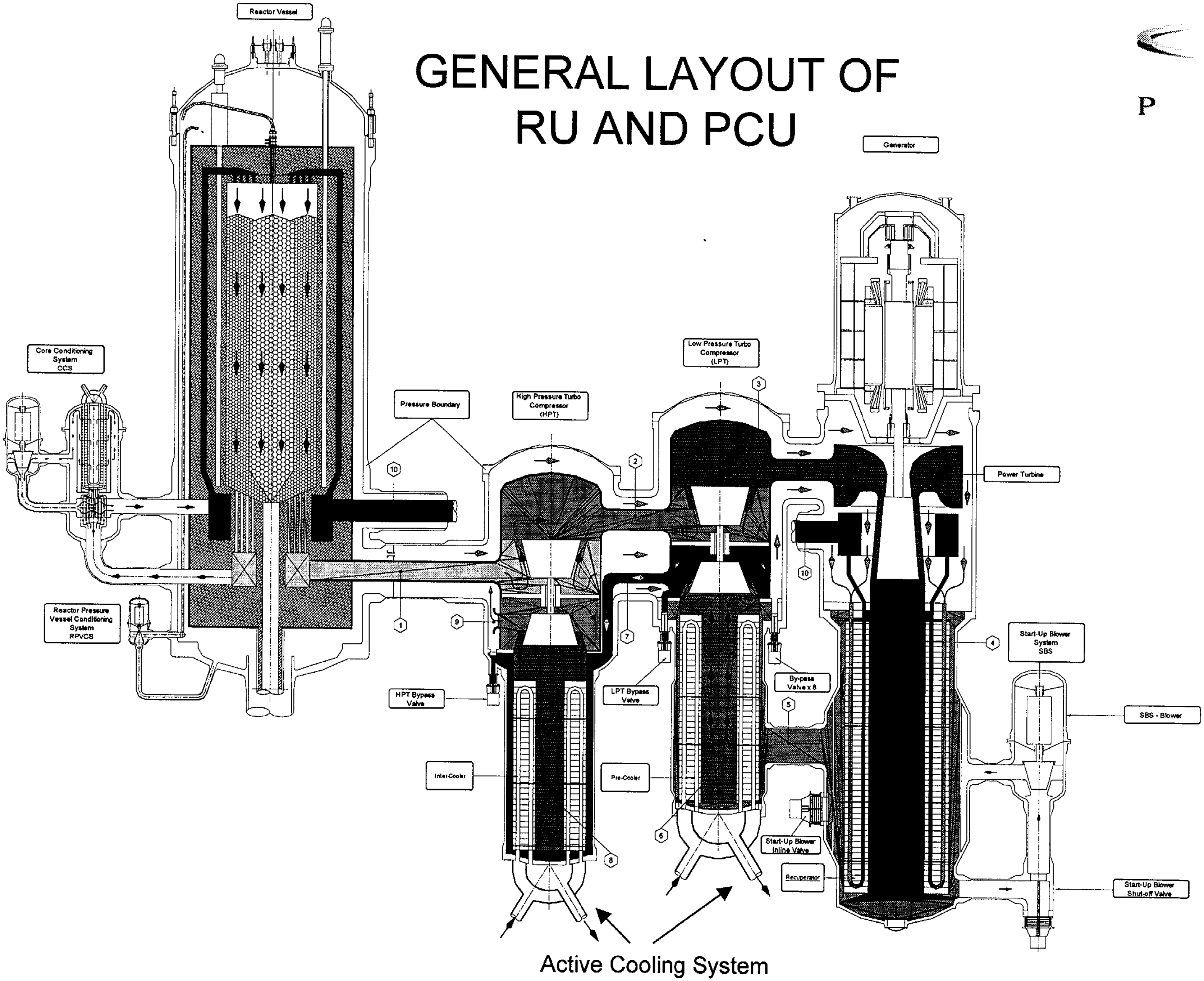
ACTIVE COOLING DURING

- Start-up
- Normal Operation
- Planned shut-down
- Unplanned shut-down
- Maintenance shut-down

REACTOR CAVITY COOLING SYSTEM (RCCS)

- Operation in active mode
- Operation in passive mode

GENERAL LAYOUT OF RU AND PCU



START-UP (Equilibrium core)

- In the start-up mode the reactor is cooled by the start-up blower system (SBS)
- The SBS will function at power levels up to 20% of full power
- Core temperature will be between 750 C and 900 C
- Heat removed via the pre- and intercoolers to the ultimate heat sink
- Heat removal quantity is regulated by blower speed and bypass valve manipulation
- The PTG is synchronized at low power levels

NORMAL OPERATION

- The Brayton cycle removes heat by cycling the helium through the core and the PCU
- Heat removed is proportional to the helium inventory
- The reactor power will adjust to the helium inventory level
- Below 40% of full power, control will be by opening the compressor bypass valves

PLANNED SHUTDOWN

- Power is reduced using helium inventory control
- Reactor is shutdown normally
- System is separated from the grid
- Brayton cycle collapses by opening of bypass valves
- SBS is activated to remove decay energy
- Heat is removed by Active Cooling System

UNPLANNED SHUTDOWN

- On reactor scram the Brayton cycle collapses by opening the bypass valves
- On load rejection the generator bypass valves prevent over-speeding, reactor is rundown and inventory is reduced
- Within a few minutes the SBS is started for continued active heat removal

MAINTENANCE SHUTDOWN

- The Reactor Unit Conditioning System (RUCS) is prepared for operation while the SBS cools the core.
- Heat removal is transferred to the RUCS and the system pressure is reduced to atmospheric as soon as convenient.
- The RUCS keeps the core at the required temperature while PCU maintenance is in progress

RCCS in Active Mode

- Coolant is pumped by pumps in the buffer circuit through an anti-syphoning device into the RCCS water pipes through three separate manifolds. Water enters and leaves through the top
- The system is sized to enable the removal of the full decay heat load after other means of cooling are disengaged

RCCS in Passive Cooling Mode

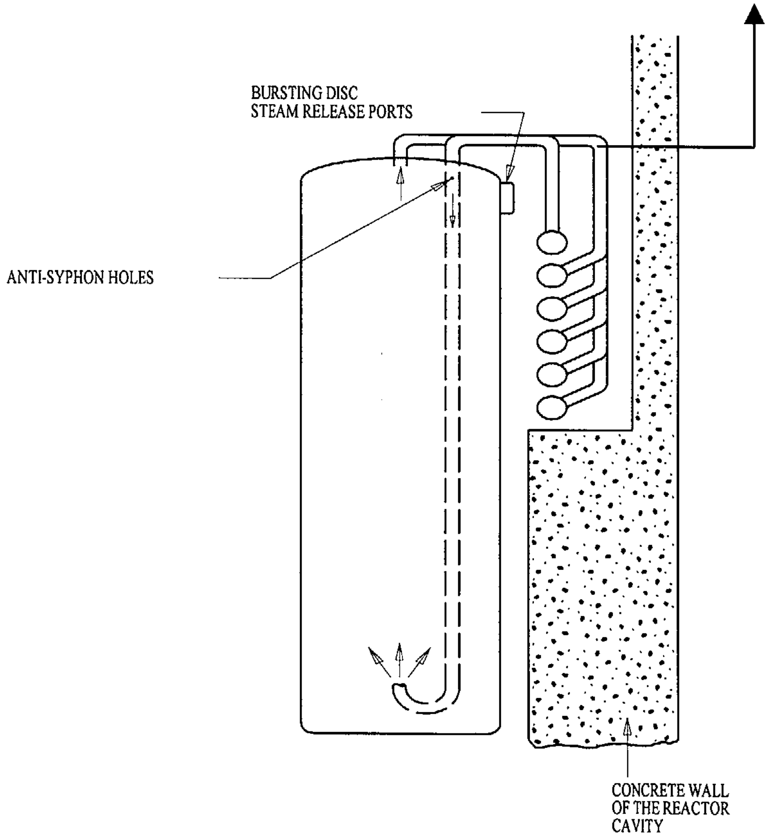
- Without the Brayton cycle, the SBS or the RUCS available all cooling is done by the RCCS
- The RCCS removes heat from the cavity during normal operation by circulating water at low volumes through the RCCS pipes
- The RCCS contains sufficient water to allow passive heat removal for about 5 days through boil-off.
- Defence in Depth is provided by the thermal capacity in the building and surroundings.
- There is no need for immediate operator actions.

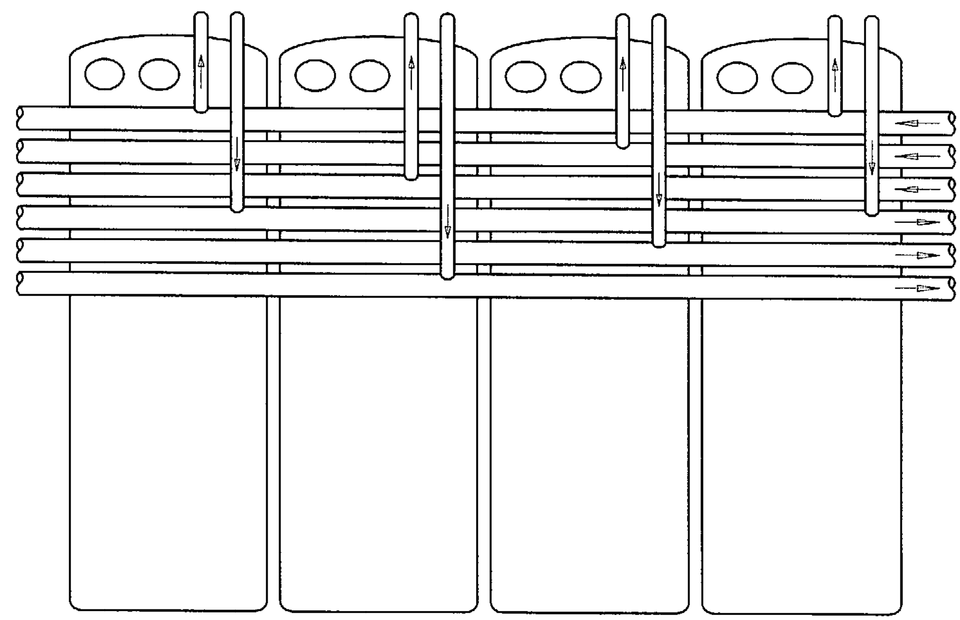
Passive Cooling After an Event

- In the case of a pressurised or depressurised loss of forced cooling and assuming the active system is unavailable, the water in the RCCS will heat up over time until boiling off will commence. A rupture disc in the system will open the path to the atmosphere to enable water vapour to escape.

Arrangement of Pipes and Headers

Bursting discs release vapor from cavity

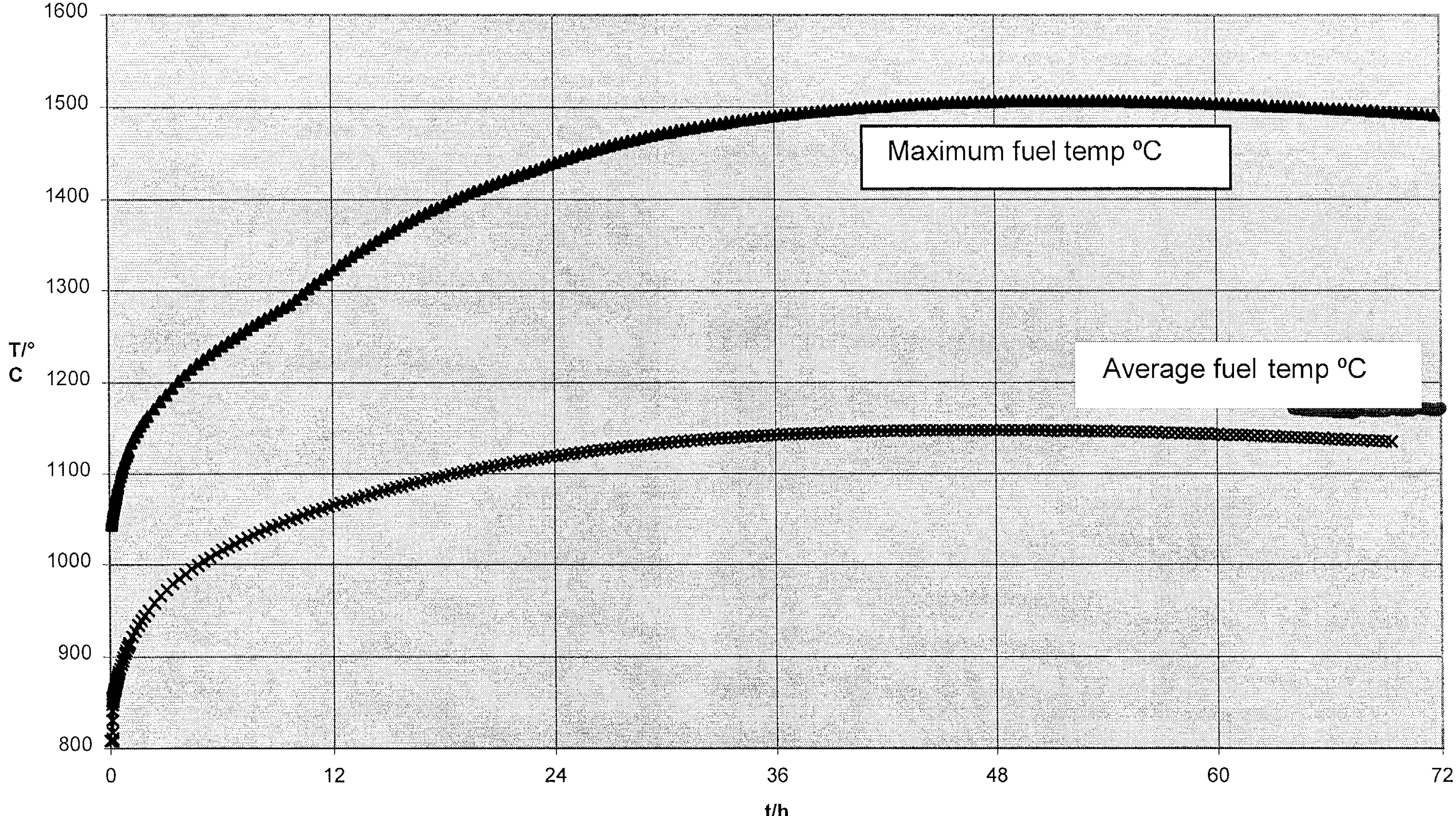




Temperature Calculations

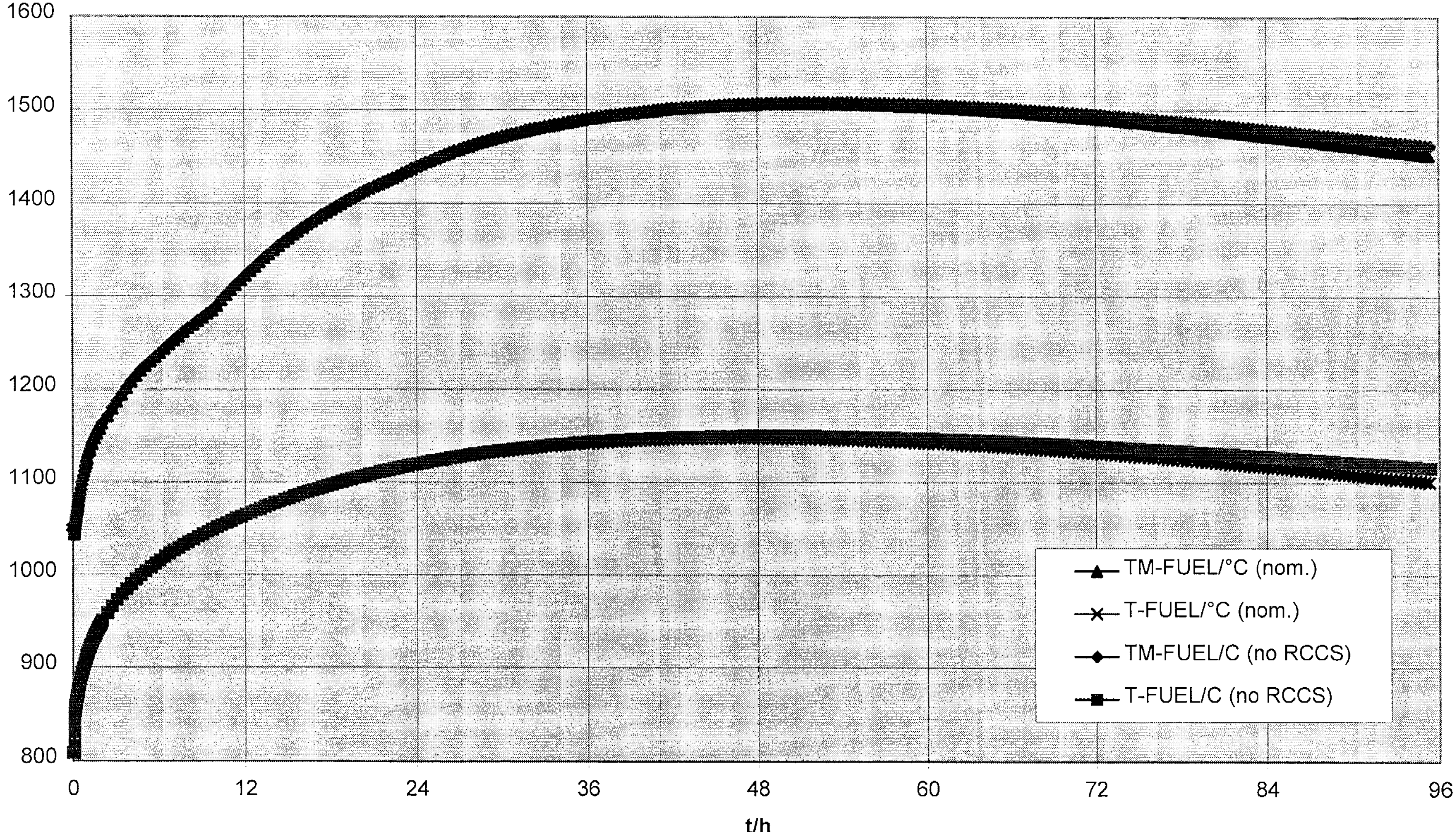
- Using a neutronics code coupled with a heat transport code, calculations on the time dependent heat up of the fuel and core components were performed with the RCCS at a constant 60 C
- The codes used are VSOP coupled to Thermix and STAR CD.

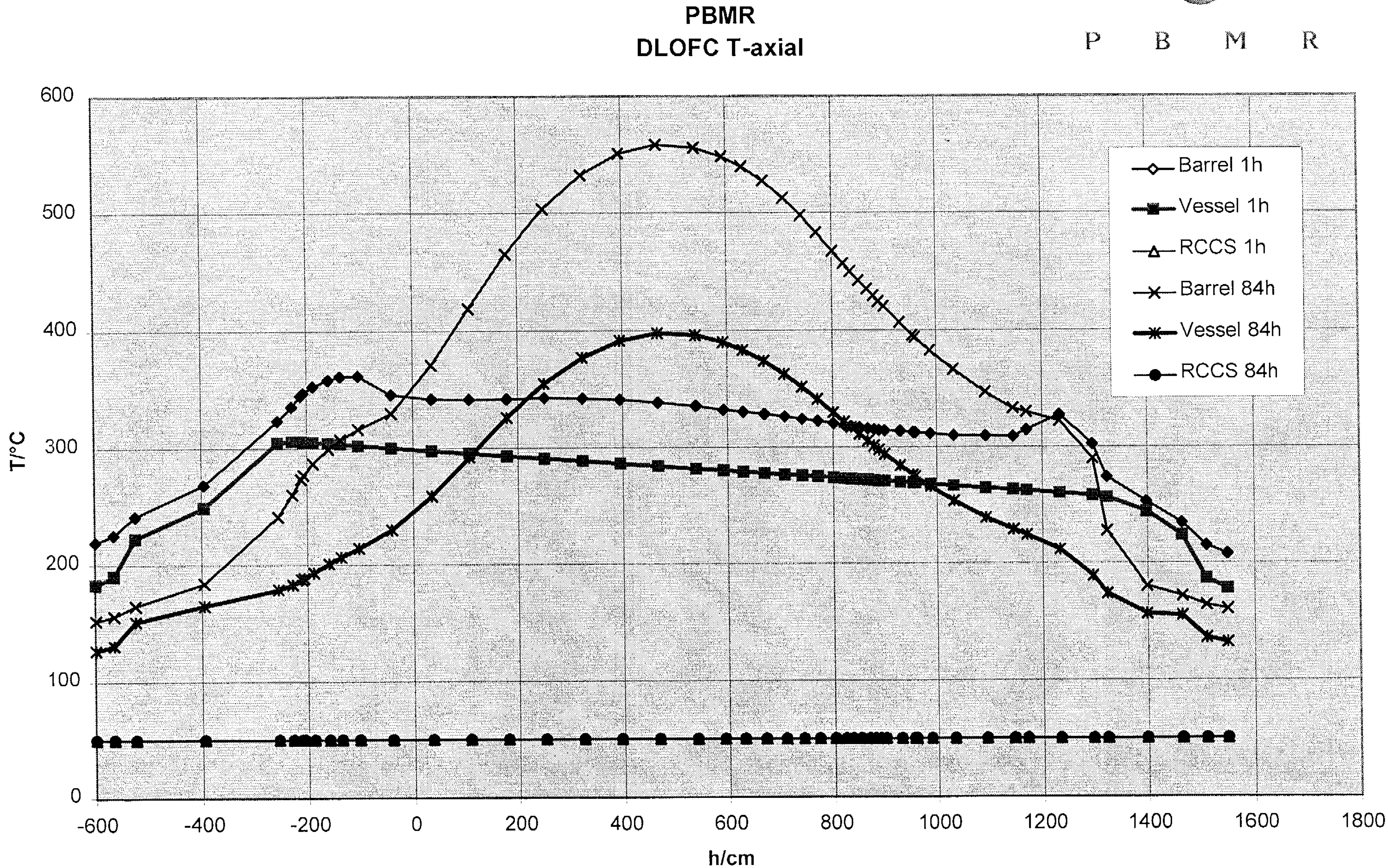
PBMR
Depressurised Loss of Forced Cooling
(Temperatures)



8/16/01

PBMR-268
DPLOFC
with and without RCCS




PBMR
DLOFC T-axial
T/°C
h/cm
Barrel 1h
Vessel 1h
RCCS 1h
Barrel 84h
Vessel 84h
RCCS 84h

MESH USED IN ANALYSIS

Proprietary Information Removed

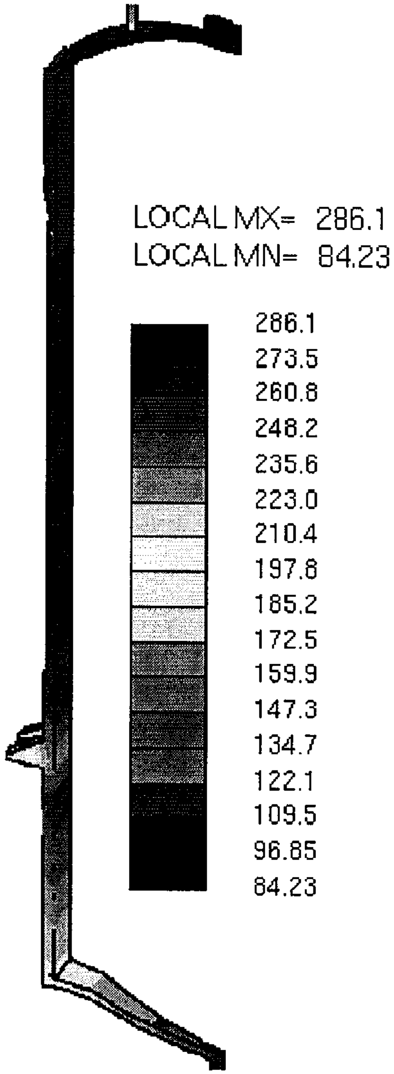
Reactor Temperature Distribution Pressurized Loss of Forced Cooling Graph

Proprietary Information Removed

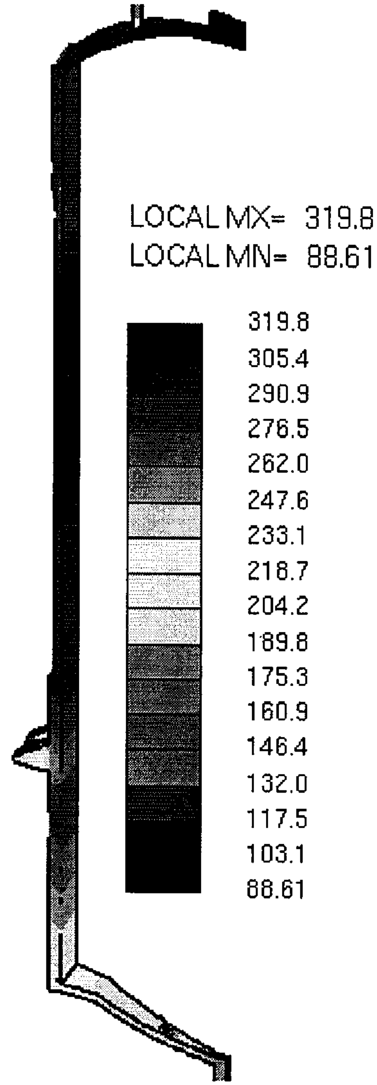
Reactor Temperature Distribution Depressurized Loss of Forced Cooling Graph without RCCS

Proprietary Information Removed

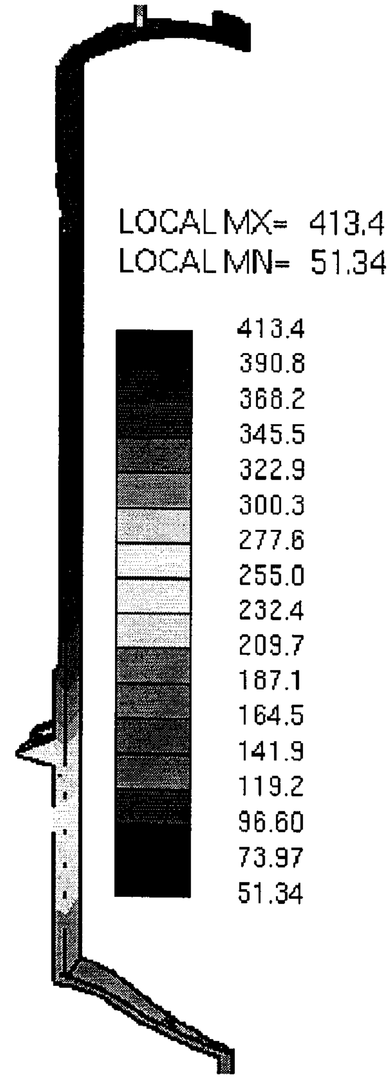
RPV Temperatures



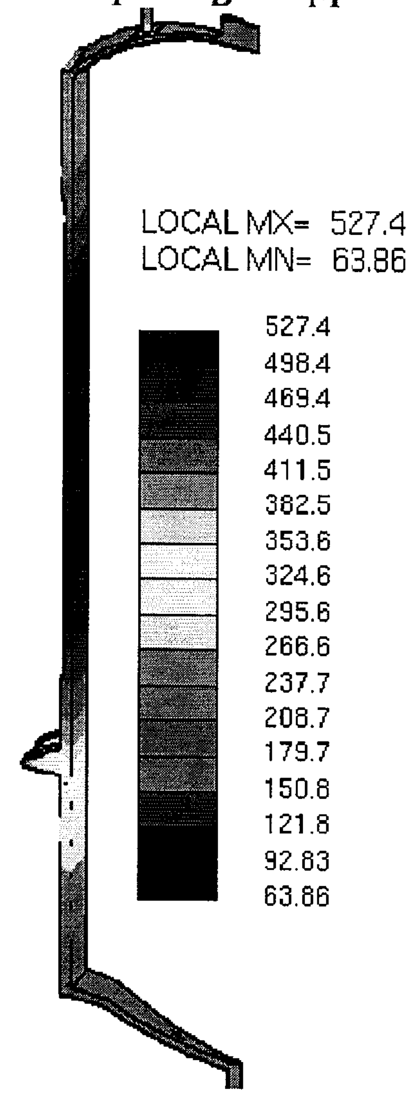
100% MCR



40% MCR



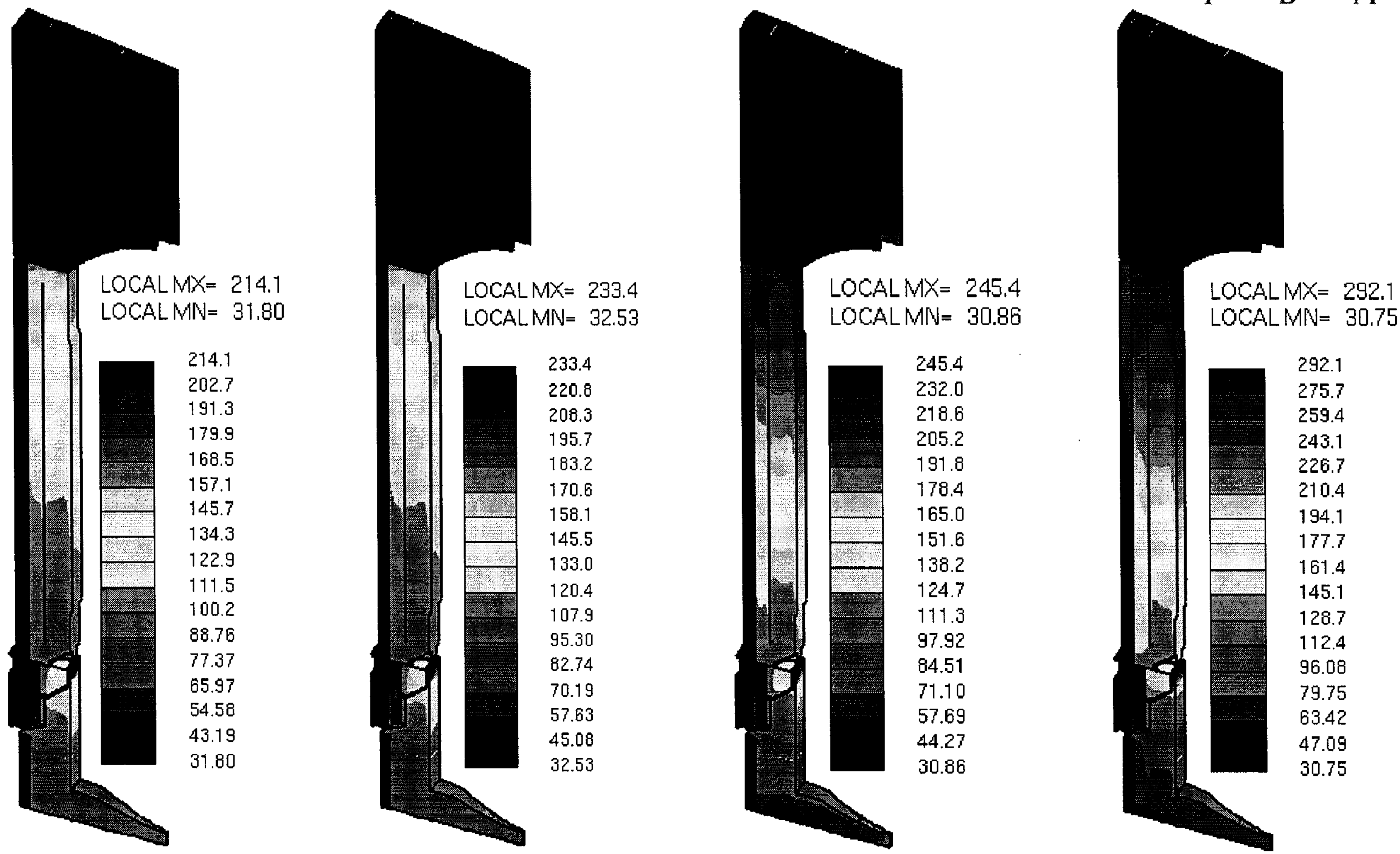
PLOFC



DLOFC

AIR TEMPERATURES

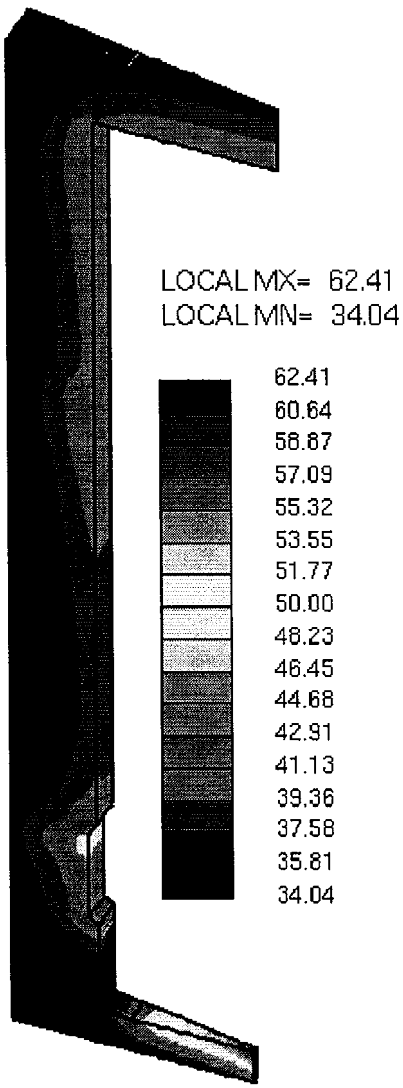
P B M R



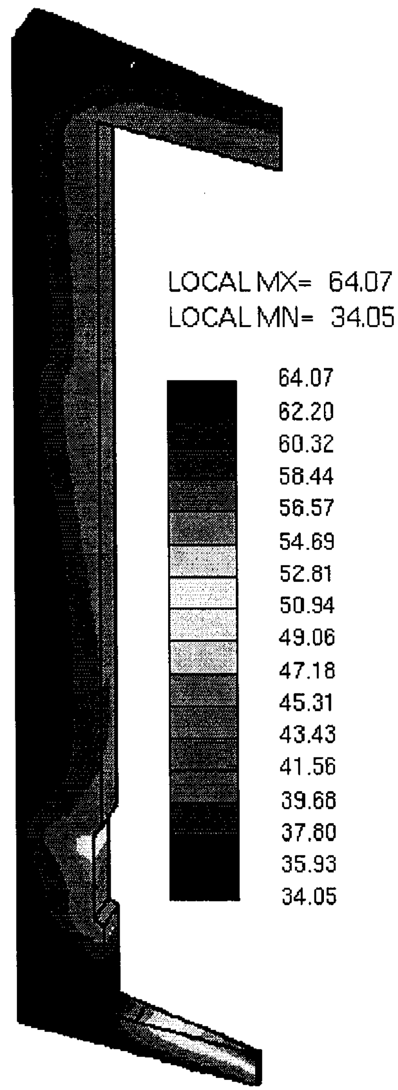
100% MCR **40% MCR** **PLOFC** **DLOFC**

CONCRETE TEMPERATURES

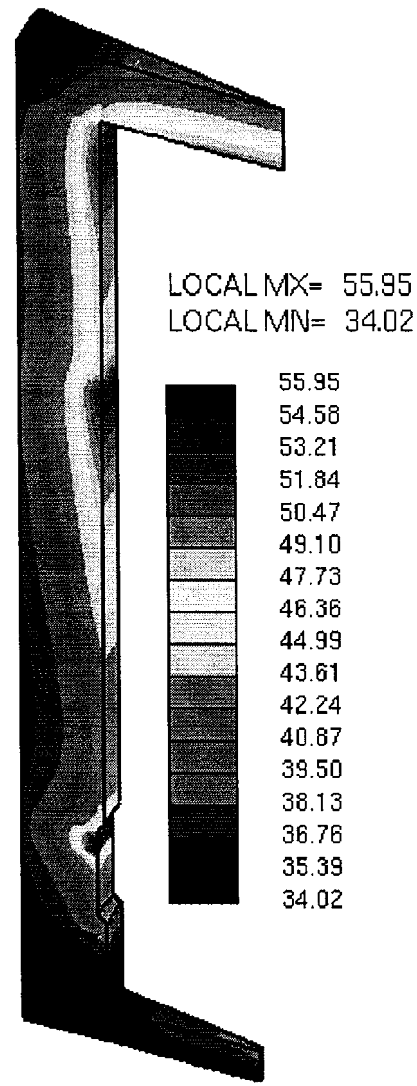
P B M R



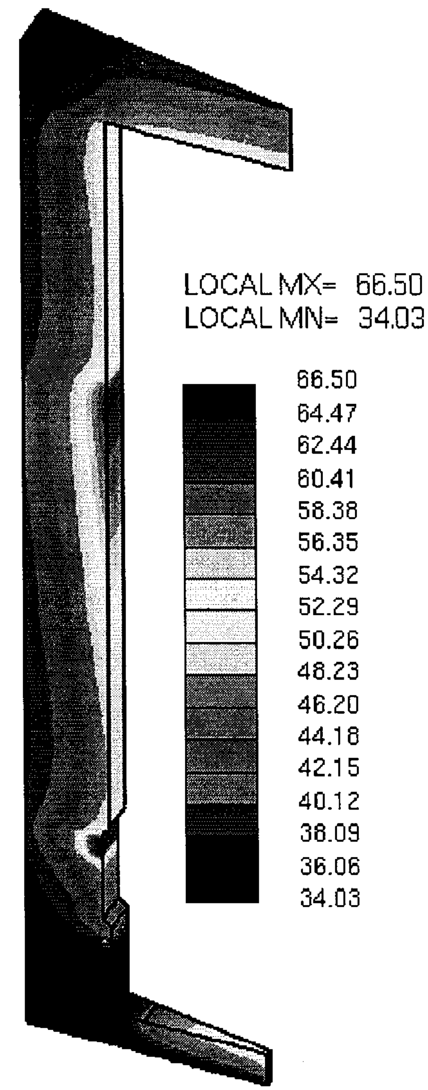
100% MCR



40% MCR



PLOFC



DLOFC

Cavity and RCCS Temperature View

Proprietary Information Removed